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Abyssal Seafloor Waste Isolation: Environmental Report

Edited by

PHILIP J. VALENT

Marine Geosciences Division

DAVID K. YOUNG

Ocean Sciences Branch
Oceanography Division

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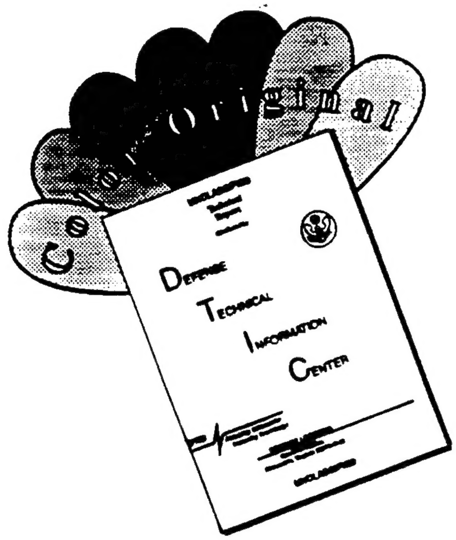

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The Naval Research Laboratory (NRL), with industry and academic participation, has completed a study of the concept of isolating industrial wastes (i.e., sewage sludge, fly ash from municipal incinerators, and dredged material) on the oceans' abyssal seafloor. In this study, the advantages and disadvantages, economic viability, and environmental impacts of potential isolation techniques were identified and assessed.

The technical and economic assessment portion of the study is reported in detail in five NRL Contract Reports. Four of these, prepared by Oceaneering Technologies, Inc., report the results of technical analyses of five techniques for transporting wastes through the water column and emplacing wastes within an easily monitored area on the abyssal seafloor. Three of these techniques are shown to offer technically sound and economically comparable options for emplacement of wastes. The fifth report, by the Marine Policy Center, Woods Hole Oceanographic Institution, shows these three technically viable options to offer cost effective waste management options when compared with present-day waste management techniques in higher-priced areas, such as the New York/New Jersey area. The results of the technical and economic assessment reports are summarized in this report in Section 1.4.1, Engineering Concepts.

The environmental assessment portion of the study sought first to identify optimal areas that maximize environmental isolation of wastes on the abyssal seafloor, and second, to assess impact of proposed waste emplacement on such optimal areas. A PC-based site assessment model was developed to quantitatively compare the suitability of

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1° squares of the seafloor for waste isolation. Included in the analysis were environmental and anthropogenic factors. Areas in the Hatteras Abyssal Plain (Atlantic) and the abyssal hills area west of southern California (Pacific) were shown to be the most suitable, while less suitable areas were identified in the Gulf of Mexico. Contaminants in the waste materials are expected to remain adsorbed to sediment particles already part of the waste, or to become adsorbed to sediment particles settling to the seafloor or already on the seafloor. Waste isolation sites would be selected where near-bottom currents are expected to be too low to resuspend the sediments, even recently deposited clay particles. Should any contaminants escape this natural filter, advection and diffusion of dissolved contaminants by deep-ocean currents is not a likely possibility because physical oceanography numerical experiments show the contaminants to be confined to water strata deeper than 1000 m for at least 2 and probably as long as 200 years in the western North Atlantic and longer still in the eastern North Pacific.

Biological and chemical conceptual and numerical models describing the impact of emplacement of large quantities of organic wastes on the abyssal seafloor were developed. The biologic model showed that existing fauna would be wiped out in the immediate area of a waste mound, but would be replaced quickly by a less diverse benthic community. Return of the benthic community to a new equilibrium condition can be expected to take hundreds to thousands of years. The geochemical model showed geochemical processes in the original seafloor to be profoundly altered for thousands to tens-of-thousands of years. Such profound geochemical impact in the immediate locale of a waste isolation site is expected to stay local to the site. Contaminants in the waste materials adsorbed to sediment particles may enter the deep-sea food chain via deposit-feeding animals. Only one potential pathway for contaminants to leave the abyssal ocean depths has been identified: transport in the yolks of eggs of demersal fish species. The eggs (gonads) of some fish species are known to rise to shallower water depths where they could be consumed by other species closer to food chains utilized by humans. The potential for measurable transport via this pathway is believed negligible, but certainly merits thorough evaluation.

In conclusion, the abyssal seafloor waste isolation concept is technically feasible and cost effective for many waste sources, and is potentially acceptable from an environmental point of view.

CONTRIBUTORS

Dr. Frederick Bowles, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Curtis A. Collins, Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943.

Mr. Martin G. Fagot, formerly Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Kathleen M. Fischer, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Peter Fleischer, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Patrick Gallacher, Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Albert W. Green, Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Richard A. Jahnke, Skidaway Institute of Oceanography, University of Georgia, Savannah, GA 31411.

Dr. Woo-Yeol Jung, Marine Geosciences Division, Naval Research Laboratory, Washington, D.C. 20375.

Dr. Robert A. Lamontagne, Chemistry Division, Naval Research Laboratory, Washington, D.C. 20375.

Dr. Robert E. Pellenbarg, Chemistry Division, Naval Research Laboratory, Washington, D.C. 20375.

Dr. Pavel Pistek, Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Michael D. Richardson, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Gilbert T. Rowe, Department of Oceanography, Texas A&M University, College Station, TX 77843.

Ms. Mary M. Rowe, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Mr. William B. Sawyer, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Philip J. Valent, Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

Dr. Peter R. Vogt, Marine Geosciences Division, Naval Research Laboratory, Washington, D.C. 20375

Dr. Alan W. Webb, Condensed Matter and Radiation Sciences Division, Naval Research Laboratory, Washington, D.C. 20375.

Dr. David K. Young, Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529.

The work reported herein is part of the project "Technical and Economic Assessment of Storage of Industrial Waste on Abyssal Plains," managed by the Naval Research Laboratory and sponsored by the Strategic Environmental Research and Development Program.

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When initiating this project, the principal investigators organized an Executive Review Committee (ERC) including Drs. Fred Grassle, Rutgers University; Larry Swanson, State University of New York at Stony Brook; Peter Jumars, University of Washington; and Fred Spiess, Scripps Institution of Oceanography with the task of overseeing the project technical and scientific direction. Largely because of the short timeframe for carrying out the project work (i.e., 10 months, including negotiation and letting of three contracts), the ERC was not tasked to the degree originally planned and the committee did not have the opportunity to influence direction of the project to the extent hoped for by the ERC and the project principal investigators. However, the ERC did contribute significantly to this project via review and comment on technical and scientific issues in the project plan, in the minutes of project team meetings, and in the findings, conclusions, and recommendations of this environmental report. The authors are particularly grateful to Drs. Larry Swanson and Fred Grassle for their time and very valuable experience and insights conveyed to the Principal Investigator in meetings at their institutions.

The authors also express their appreciation to Mr. Tom Wright, U.S. Army Waterways Experiment Station, for providing a "short course" for Phil Valent and Dave Young on present regulations and testing requirements for dredged material. Mr. Frank Roethel, State University of New York at Stony Brook, provided significant valuable insight and literature into the nature of ash from municipal incinerators and the environmental problem associated with the fly ash component. Dr. Fred Sayles, Woods Hole Oceanographic Institution, provided reports from the Woods Hole Oceanographic Institution workshops into the parent waste emplacement scheme that preceded and led to formulating this SERDP project. We also thank Dr. Jonathan Amson and Messrs. David Redford and Tom Chase of the Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, for their technical reviews and suggestions for improvement of our draft report.

ABSTRACT

The Naval Research Laboratory (NRL), with industry and academic participation, has completed a study of the concept of isolating industrial wastes (i.e., sewage sludge, fly ash from municipal incinerators, and dredged material) on the oceans' abyssal seafloor. In this study, the advantages and disadvantages, economic viability, and environmental impacts of potential isolation techniques were identified and assessed.

The technical and economic assessment portion of the study is reported in detail in five NRL Contract Reports. Four of these, prepared by Oceaneering Technologies, Inc., report the results of technical analyses of five techniques for transporting wastes through the water column and emplacing wastes within an easily monitored area on the abyssal seafloor. Three of these techniques are shown to offer technically sound and economically comparable options for emplacement of wastes. The fifth report, by the Marine Policy Center, Woods Hole Oceanographic Institution, shows these three technically viable options to offer cost effective waste management options when compared with present-day waste management techniques in higher-priced areas, such as the New York-New Jersey area. The results of the technical and economic assessment reports are summarized in this report in Section 1.4.1, **Engineering Concepts**.

The environmental assessment portion of the study sought, first, to identify optimal areas which maximize environmental isolation of wastes on the abyssal seafloor and second, to assess impact of proposed waste emplacement on such optimal areas. A PC-based site assessment model was developed to quantitatively compare the suitability of 1°-squares of the seafloor for waste isolation. Included in the analysis were environmental and anthropogenic factors. Areas in the Hatteras Abyssal Plain (Atlantic) and the abyssal hills area west of southern California (Pacific) were shown to be the most suitable, while lesser suitable areas were identified in the Gulf of Mexico. Contaminants in the waste materials are expected to remain adsorbed to sediment particles already part of the waste, or to become adsorbed to sediment particles settling to the seafloor or already on the seafloor. Waste isolation sites would be selected where near-bottom currents are expected to be too low to resuspend the sediments, even recently deposited clay particles. Should any contaminants escape this natural filter, advection and diffusion of dissolved contaminants by deep-ocean currents is not a likely possibility because physical oceanography numerical experiments show the contaminants to be confined to water strata deeper than 1000 m for at least 2 and probably as long as 200 years in the western North Atlantic and longer still in the eastern North Pacific.

Biological and chemical conceptual and numerical models describing the impact of emplacement of large quantities of organic wastes on the abyssal seafloor were developed. The biologic model showed that existing fauna would be wiped out in the immediate area of a waste mound, but would be replaced quickly by a less diverse benthic community. Return of the benthic community to a new equilibrium condition can be expected to take hundreds to thousands of years. The geochemical model showed geochemical processes in the original seafloor to be profoundly altered for thousands to tens-of-thousands of years. Such profound geochemical impact in the immediate locale of a waste isolation site is expected to stay local to the site. Contaminants in the waste materials adsorbed to sediment

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In conclusion, the abyssal seafloor waste isolation concept is technically feasible and cost effective for many waste sources, and is potentially acceptable from an environmental point of view.

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ABYSSAL SEAFLOOR WASTE ISOLATION: ENVIRONMENTAL REPORT

1.0 INTRODUCTION

1.1 OBJECTIVE AND BACKGROUND *by Philip J. Valent*

1.1.1 CONTENT

The Naval Research Laboratory (NRL), with industry and university participation, has completed a ten-month duration assessment (November 1993 through September 1994) of the concept of isolating wastes (i.e., sewage sludge, fly ash from municipal incinerators, and dredged material) on the oceans' abyssal seafloor. In this assessment the advantages, disadvantages, and economic and environmental viability of potential waste isolation techniques were identified and compared. This project was funded by the Strategic Environmental Research and Development Program (SERDP) as part of its Compliance Thrust Area. The environmental aspects of this assessment are reported herein, while the technical aspects are reported in Marcy et al. (1994) and Hightower et al. (1995a), and the economic aspects in Hightower et al. (1994) and Jin et al. (1995).

1.1.2 BACKGROUND

The disposal of sewage sludge, fly ash from municipal incinerators, and dredged material is a critical problem facing the U.S. and other nations. Presently only 17% of the U.S. municipal waste stream (sewage sludge and solid waste) is recycled, 16% is incinerated, and 67% is disposed of in landfills (EPA 1992d; 1993b). The threat to ground water resources posed by landfill disposal makes this approach increasingly undesirable (NRC 1985, p. 129; Hollister 1992, p. 128; Haag 1992). Further, the health and social problems associated with fly ash waste from incinerators is making that approach less desirable (Johnson 1989). Inaction in the maintenance dredging of contaminated sediments from shipping berths, navigation channels, and turning basins, because of concern over the environmental impact of disposing of dredged materials by present methods, is compelling maritime commerce to avoid affected U.S. ports (Haggerty 1993) and impacts adversely on U.S. military capability to rapidly deploy troops and material for protection of U.S. interests overseas. Therefore, other waste disposal options must be given serious consideration. One potential waste disposal option is the emplacement of the waste on low-energy areas of the deep-ocean floor without contamination of the overlying water column (Spencer 1991; Chryssostomidis 1991; Hollister 1992; Graham 1993; NRC 1985, p. 132; Edmond 1992; Angel 1992; Ballard 1992; Rubin 1992).

The Congress tasked the Department of Defense (DoD) in the 1993 Department of Defense Appropriation Bill, Senate Report 102–408, as part of DoD's Strategic Environmental Research and Development Program (SERDP), to:

> "...study the advantages, disadvantages, and economic viability of storing industrial waste in the abyssal plains of the ocean floor. Abyssal plains are areas of the ocean floor at depths of over 10,000 feet which are believed to be geologically stable and to experience only slight water currents. The Committee [i.e., Committee on Appropriations] understands that these characteristics may make abyssal plains viable regions for long-term storage of industrial waste. The Committee is aware of preliminary scientific discussions of this concept and feels additional study of the concept would be useful."

NRL responded to this Congressional tasking with a proposal to the FY93 SERDP to conduct a "Technical and Economic Assessment of Storage of Industrial Waste on Abyssal Plains." The NRL proposal was funded in November 1993.

1.1.3 Definition of Terms

In the course of defining and scoping this project, the intent of the terms "industrial waste" and "storing" were sought. We first determined that the "preliminary scientific discussions" identified in the Congressional language referred to the Woods Hole Oceanographic Institution study (Spencer 1991) in which the wastes described were: (1) sewage sludge, (2) fly ash from municipal incinerators, and (3) dredged material. The dredged material to be stored was assumed to be that which could not be emplaced and maintained safely in coastal waters, in other words, contaminated dredged material. The term "storing" suggests that potentially one might return to the abyssal plain waste material emplacement site to recover the waste. The participants in this study do not believe that recovery of the subject wastes from the abyssal seafloor is a technically nor economically viable option. Thus, the participants in this study chose the term "isolation" to more properly describe the intent of the project, and adopted the shortened project title "Abyssal Plains Waste Isolation (APWI)." Further, we determined that the shortened project title, "Abyssal *Plains*...," was not adequately descriptive because of acceptable isolation sites in the northeast Pacific which are in abyssal **hill** areas. This rationale is further described in Section 3.0 of this report. The title of this report, incorporating the phrase "...Abyssal **Seafloor** Waste Isolation," is our final word change to convey to the reader an accurate understanding of the ocean-isolation option assessed by this project.

1.1.4 Project Organization

The project was organized into five tasks (Fig. 1.1-1) to be carried out concurrently:

(1) **Task 1, Area Assessment:** The Area Assessment Task: (a) identified environmental characteristics of the abyssal ocean environment which impacted on suitability of a site for

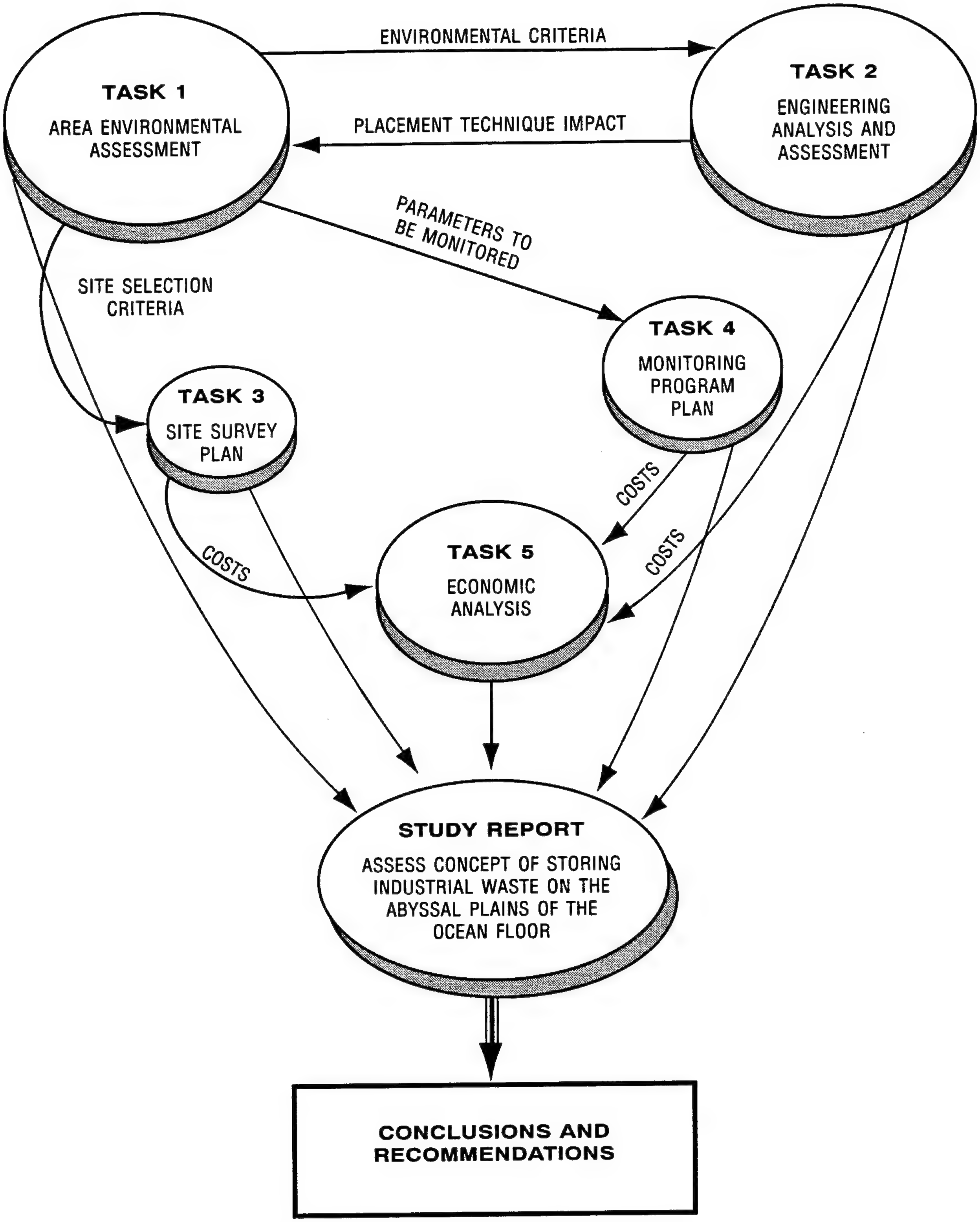

Figure 1.1-1. Task areas and task interrelationships for the SERDP Project, Technical and Economic Assessment of Storage of Industrial Waste on Abyssal Plains.

waste disposal, (b) developed a computer model for selection of potential waste sites allowing differential weighting of individual site characteristics, (c) selected five abyssal seafloor sites for in-depth analysis of the waste isolation concept, and (d) applied modified and newly-developed physical, chemical, and biological oceanography models to describe the impact of waste isolation on the abyssal ocean environment. Results of Task 1 appear in Sections 2.0, 3.0, 5.0, and 6.0 of this report.

(2) **Task 2, Engineering Analysis and Assessment:** This task performed technical assessments of five concepts for emplacing wastes on the abyssal seafloor without contamination of the overlying water column. The technical assessment considered dockside staging requirements, ship requirements, waste packaging, marine operations for transportation and disposal, and the equipment and vehicles necessary to reliably emplace waste on the abyssal seafloor. Results of Task 2 appear in the technical assessment report (Hightower et al. 1995a) and are summarized in Hightower et al. (1995b) and in Section 1.4.1 of this report, **Engineering Concepts**.

(3) **Task 3, Site Survey Plan:** The Site Survey Plan Task outlined methods and procedures for accurate description of the potential waste isolation sites in terms of the geology and physical, chemical, and biological oceanography to be analyzed and evaluated. Results of this task are to be found in Section 4.0, **Site Survey and Monitoring Plan**.

(4) **Task 4, Monitoring Program:** The Monitoring Program Task outlined short- and long-term monitoring requirements identifying: (a) parameters to be measured; (b) methods, location and frequency of sampling; (c) criteria for evaluating environmental change; and (d) estimated cost of the program. For results of Task 4, see Section 4.0, **Site Survey and Monitoring Plan**.

(5) **Task 5, Economic Analysis:** The Economic Analysis Task prepared preliminary cost assessments for loading, transporting, and emplacing each of the three waste streams by each of the four technically viable emplacement concepts (Hightower et al. 1994). These port-to-site costs, together with costs projected for source-to-port, provide cost projections for comparison with the costs of present practice waste disposal methods (Jin et al. 1995).

1.1.5 Organization of this Environmental Report

This report first provides a synopsis of environmental regulations, both U.S. and international, impacting on waste isolation on the abyssal seafloor in Section 1.2. This review of applicable regulations is followed by a physical description of the waste streams considered, their geographic source distribution, and quantities in Section 1.3. Section 1.4 describes aspects of the probable waste transport, emplacement, and containment concepts likely to impact on the environmental assessment; and Section 1.5 provides a summary of findings from some previous studies relevant to the abyssal seafloor waste isolation option.

Section 2.0 is a tutorial review of physical oceanography (2.1), geology and geophysics (2.2), geochemistry (2.3), and ecology (2.4) of the northwest Atlantic, Gulf of Mexico, and northeast Pacific, with particular attention paid to the abyssal seafloor and near- seafloor environment. Given this tutorial on the environment, Section 3.0 develops a rationale, procedure, and analytical programmed model for selection of abyssal waste isolation sites. Section 4.0 proceeds from this methodology for site selection to a description of plans for gathering

necessary in situ data for such site selection, and for monitoring these sites before, during, and after emplacement of waste to ensure that isolation of all emplaced components from the euphotic zone will be complete. Section 5.0 presents results of initial attempts to predict the impact of waste emplacement on the abyssal environment based largely on modeling work performed in this project: (1) in Section 5.1, based on model description of the **physical oceanography**, at basin scale and at the scale of a plume generated by emplacement; (2) in Section 5.2, based on understanding of **sediment mass transport** at abyssal seafloor sites; (3) in Section 5.3, based on extrapolation of understanding of **mobility of contaminants** in the shallow-ocean environment to the abyssal ocean and on modeling of **geochemical changes** to occur in the sediments as a result of waste emplacement; and (4) in Section 5.4, based on modeling of fluxes in the abyssal ocean-ecosystem **food chains** resulting from waste emplacement and extrapolated from observations of episodic depositional events at abyssal ocean depths.

1.1.6 Contributors to this Report

Although authors of this report are identified as having the primary responsibility for writing individual sections, the report as a whole represents a joint collaborative effort among all contributors. Contributors participated in a series of one- to three-day workshops at NRL-Stennis Space Center which were held approximately once per month from February through September, 1994. The main foci of these workshops were environmental issues, generally relating to the **Area Assessment Task**, the **Site Survey Plan Task** and the **Monitoring Program Task**. Task Leaders David Young and Michael Richardson served as organizers of these workshops chaired by the Principal Investigator, Philip Valent. William Sawyer served as Executive Secretary on all workshops and was responsible for keeping records of proceedings and distributing minutes to all participants.

At various times during these workshops, engineers and economists working on the **Engineering Analyses and Assessment Task** and the **Economic Analysis Task** presented their findings and participated in workshop activities. They contributed much to workshop proceedings and to the understanding of engineering and economic considerations by contributors of this environmental report. These participants who are acknowledged and thanked for their help, include: Michael Hightower, William Richards, and April Marcy, all of Oceaneering Technologies, Inc., Upper Marlboro, MD, and Jin and Hauke Kite-Powell of the Marine Policy Center, Woods Hole Oceanographic Institution.

1.2 Environmental Regulations *by William B. Sawyer*

Since the implementation of the Marine Protection, Research, and Sanctuaries Act, also known as the Ocean-Dumping Act (MPRSA 1972, 1974, 1977), and the subsequent Ocean-Dumping Ban Act (ODBA 1988), ocean disposal of sewage sludge and most other wastes, excluding dredged materials, ceased (the ocean disposal of sewage sludge continued at the 106-mile site off New York City until 1992). The ocean-disposal practice for dredged materials falls under the auspices of the U.S. Army Corps of Engineers (COE) and the U.S. Environmental Protection Agency (EPA) and only dredged materials passing EPA criteria

may be permitted to be disposed of in oceanic waters within the jurisdiction of the United States at designated sites. Table 1.2-1 delineates the individual and joint responsibilities of these governmental organizations. This section will focus on the regulations dealing with dredged material disposal in the ocean while realizing that: (1) current regulations prohibit sewage sludge and municipal incinerator fly ash ocean-disposal options, and (2) amending the ODBA would be required for abyssal seafloor waste isolation management for these materials to become a reality. Additionally, approval of a permit under section §220.3 of the Marine Protection, Research, and Sanctuaries Act would be required (MPRSA 1972).

Ocean disposal of dredged materials is regulated in accordance with the ocean-dumping regulations and subsequent guidance provided in: (1) "*Evaluating Environmental Effects of Dredge Material Management Alternatives – A Technical Framework*," (EPA 1992a) and (2) "*Evaluation of Dredged Material Proposed For Ocean Disposal – Testing Manual*," also known as the "Green Book" or "Testing Manual" (EPA 1991a). The Technical Framework document "is designed to facilitate the environmental evaluations that meet the substantive and procedural requirements of National Environmental Policy Act (NEPA), the Marine Protection, Research, and Sanctuaries Act (MPRSA), and the Clean Water Act (CWA), and to enhance interagency coordination and consistency in evaluating management alternatives" (EPA 1994, pp 87–88). The "Ocean Testing Manual" contains technical guidance for determining the suitability of dredged material for ocean disposal through chemical, physical, and biological evaluations (EPA 1991a).

Dredged materials disposed in inland, estuarine, and coastal waters of the U.S. are regulated within the CWA while material disposed of in coastal and open-ocean waters of the U.S. are covered within the MPRSA. The CWA jurisdiction begins at the "baseline" of the territorial sea, and extends inland, but includes material used as fill such as for beach restoration from the baseline seaward within the territorial sea. The MPRSA jurisdiction extends from the "baseline," seaward beyond the contiguous zone (from 3–12 nmi offshore) and for legal purposes anywhere in all oceans when dealing with vessels leaving a U.S. port for the purpose of dumping wastes, while excluding dredged material used as fill in coastal waters. Current disposal practices do not allow placing material failing to meet certain effects-based criteria in waters either inland or seaward of the "baseline" of the territorial sea. In those cases where initial evaluation indicates that the effects-based criteria are not met, management actions should be considered to see if the dredged material can be brought into compliance. If the material can be brought into compliance, ocean disposal can be accomplished; if not, ocean disposal is not permitted, and other disposal management strategies (special management) must be evaluated.

Disposal of dredged materials in the open ocean is subject to permit at designated ocean-disposal sites. Currently there are 109 designated sites within the U.S. ocean waters. These sites are selected via the mandates within the MPRSA, which "avoid unacceptable, adverse impacts on biota and other amenities." Factors for selection of disposal sites are presented within the MPRSA (see Section 3.1, **Rationale and Procedure for Site Selection Process**). Additionally, "wherever feasible," open-water sites will be selected beyond the continental shelf break (~200 m water depth), and at sites previously used, unless a "significant adverse impact" is indicated (EPA 1991a). An environmental impact statement for a proposed disposal site will be prepared when required by the EPA. The EPA Office

Table 1.2-1 Roles and Responsibilities of EPA and COE in Managing the Ocean Disposal of Dredged Materials Under MPRSA.

EPA Responsibilities	**COE Responsibilities**
Designating ocean sites for dredged material	Issuing permits for the transportation and disposal of the dredged material
Regulation of times, rates, and methods and testing requirements of dredged material disposal and the quantity and type of dredged material that may be disposed of at a site	Permit compliance
Modifications in site use or designation and/or designation of the ocean dredged material disposal site	
Must concur in writing on COE permits	

Joint Responsibilities

Evaluating the effect of dredged material disposal at the site

Developing and implementing site management plans

Developing and implementing effective monitoring programs for the site

of Water and COE are currently developing a new ocean-disposal site designation, management, and monitoring guidance document which will include ocean-disposal site management plans (EPA 1994).

Testing and evaluation of dredged material is required prior to receipt/denial of an ocean-dumping permit. The national guidance document for this testing, the "Green Book" (EPA 1991a), emphasizes biological effects-based tests to determine the environmental impact and/or suitability for disposal of the dredged material at designated ocean-disposal sites. The "Green Book" guidance must be consulted and utilized for ocean disposal of dredged material.[1]

The Green Book applies a four-tiered and two-pathway testing approach, shown in Figure 1.2-1, to determine the ecological impact to the water column and the benthic environment. As indicated in this guidance document, each successive tier applies more detailed, rigorous, and expensive testing procedures. After each tier is completed, one of three determinations can be made: (1) the criteria in the regulations are met, ocean disposal is supported, no additional testing is necessary; (2) the evaluation is inconclusive, ocean disposal is not supported, testing must proceed to the next tier; or (3) the regulatory criteria are not met; ocean disposal is not supported.

The Green Book (EPA 1991a, p 3-1) distinguishes between reference and control sediments for testing procedures. Identical tests are performed on the reference sediment, the control sediment, and the dredged material before the determination to dispose of the dredged material in the ocean, or not dispose, can be accomplished. The "...control sediment is a natural sediment essentially free of contaminants" and "fully compatible with the needs of the test organisms such that it have no discernible influence on the response being measured in the test." The reference sediment is "...a sediment, substantially free of contaminants, that is as similar to the grain size of the dredged material and the sediment at the disposal site as practical, and reflects conditions that would exist in the vicinity of the disposal site had no dredge-material disposal ever occurred, but had all other influences on sediment condition taken place."

The initial phase in Tier I involves the evaluation of all existing information regarding the disposal site, the dredged material, contaminants of concern in the dredged material, past physical, chemical, and biological studies, etc. Certain exclusionary criteria, such as "...the dredged material is clean sand; is to be used for beach restoration; or is far removed from all known sources of pollution," allow for the direct disposal and/or beneficial reuse of the dredged material (EPA 1991a).

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[1] The "Green Book" guidance determines a dredged material to be either suitable or not suitable for ocean disposal. The EPA Region II (New York) requires additional measures to those of the national Green Book, creating a third category of dredged material, that suitable for restricted ocean disposal. The three categories under Region II are: (1) "suitable for unrestricted ocean disposal, . . ., use as capping material, . . ."; (2) "suitable for restricted ocean disposal, i.e., disposal with capping or in burrow pit or containment island; and (3) unsuitable for unrestricted or restricted ocean disposal, may be suitable for burrow pit, containment island or upland disposal, or could result in no dredging."

EVALUATION OF EXISTING INFORMATION				TIER 1
WATER COLUMN		BENTHIC		
	WATER COLUMN TOXICITY	BENTHIC TOXICITY	BENTHIC BIOACCUMULATION	
WATER QUALITY CRITERIA			THEORETICAL BIOACCUMULATION POTENTIAL	TIER 2 (CHEMISTRY)
ELUTRIATE TEST	96 HOUR TOXICITY TEST	10 DAY TOXICITY TEST	28 DAY BIOACCUMULATION ASSAY	TIER 3 (BIOLOGY)
CASE SPECIFIC TESTING AND EVALUATION				TIER 4

Figure 1.2-1. EPA/COE tiered testing for dredged material contaminant evaluation.

The "...three specific end points used under the Green Book effects-based testing include water quality criteria (WQC), toxicity, and bioaccumulation" (EPA 1991a). In Tier II, the marine WQC established by the EPA are compared to levels detected within an aliquot of the dredged material mixed with seawater and allowed to settle out. The limiting permissible concentration (LPC), is defined as that concentration which "...will not exceed applicable marine WQC after allowing for initial mixing." If levels exceed the WQC for a given contaminant, the material cannot be disposed in the ocean. The "...contaminants of concern cannot exceed the marine WQC outside the site boundary any time, after allowing for initial mixing..." (designated disposal site), "...or inside the site boundary after allowing for a 4-hr initial mixing period." (EPA 1991a, pp 2–5, 5-1).

Additionally water column bioassays are used to determine the effects of the dissolved and suspended phases of the dredged material contaminants on organisms. An elutriate solution of the dredged material is used to expose "...species of phytoplankton and zooplankton, crustacean or mollusc, and fish." Further, "The material meets the water column criteria if, after allowing for initial mixing, the concentration of dredged material within the site boundary does not exceed a toxicity threshold of 1% of the LC_{50} (that concentration which kills 50% of the test organisms), or outside the boundary at any time" (EPA 1991a).

The benthic portion of the test in Tier II begins with the theoretical bioaccumulation potential (TBP) which estimates the uptake of certain nonpolar organic compounds in the dredged material and the calculated TBP for a test organism.

Testing of the solid phase of the dredged material begins in Tier III with the 10-day toxicity test. Certain "...filter-feeding, deposit-feeding, and burrowing organisms" are exposed to the dredged materials for a 10-day period, and the subsequent mortality rate is determined. The mortality rate cannot exceed "...that of a reference sediment by more than 20% for amphipods" (EPA 1991a, p 6-2), (one of the recommended sensitive taxa for this test). The Tier III test is used to determine the effects of all pollutants in the sediment.

The 28-day bioaccumulation test, in Tier III testing, is used to determine the bioavailability of contaminants in the sediment. The Green Book "...recommends using a burrowing polychaete and a deposit-feeding bivalve mollusc" (EPA 1991a, pp 2–8). Tissue bioassays are analyzed from the organisms following the 28-day exposure to determine the presence of bioaccumulative compounds, and then compared to reference sediment concentrations and evaluated based on several factors. The levels are compared to the U.S. Food and Drug Administration (FDA) Action Levels for Poisonous or Deleterious Substances in Fish and Shellfish for Human Food, where levels for these contaminants have been previously set (EPA 1991a, pp 3–12). If USFDA action levels are not exceeded in animals exposed to the dredged material, when statistically compared to those animals exposed to the reference sediment, the material may be ocean disposed. If the difference between the dredged material and the reference sediment is determined to be statistically significant, subjective factors are then considered to determine if the LPC is met.

We note here, the organisms used for the toxicity and bioaccumulation tests described above are all shallow-water varieties. Testing for toxicity and bioaccumulation at abyssal seafloor depths must be performed using abyssal organisms. Thiel et al. 1994, note that the retrieving and utilizing of abyssal organisms for studying the effects of toxicity and

bioaccumulation is technically feasible but logistically very difficult and costly. In this introductory study we have not attempted to identify abyssal organisms suitable for toxicity and bioaccumulation testing.

In a recent review of the Green Book, the Science Advisory Board (SAB) recommended "...that EPA should: (1) revise the tiered testing procedure to further emphasize reducing uncertainty as the level of tiered testing increases, (2) provide improved guidance on the interpretation of the bioaccumulation test results, (3) clarify how sediment quality criteria (SQC) will be incorporated into the tiered-testing approach, (4) require testing of appropriately sensitive species, and (5) include appropriately sensitive test species measures of chronic sublethal effects" (EPA 1994, p 85). The EPA and COE, in addressing the issues of the SAB, will implement the use of "...sediment quality criteria..." in Tier II testing in future revisions of the Green Book and continue to improve other aspects of dredged material testing.

Materials prohibited for disposal in the ocean include: "...high-level, radioactive wastes; materials in whatever form (including without limitation, solids, liquids, semisolids, gases, or organisms) produced or used for radiological, chemical, or biological warfare; materials insufficiently described by the applicant in terms of their compositions and properties to permit application of the environmental impact criteria of the MPRSA; persistent inert synthetic or natural materials which may float or remain in suspension in the ocean in such a manner that they may interfere with fishing, navigation, or other legitimate uses of the ocean" (MPRSA 1972, §227).

Further, "Subject to exclusions of the MPRSA, ocean dumping, or transportation for dumping, of material containing the following constituents as other than trace contaminants will not be approved on other than an emergency basis, as determined by the MPRSA contaminant evaluation process; organohalogen compounds; mercury and mercury compounds; cadmium and cadmium compounds; oil of any kind or in any form, including but not limited to petroleum, oil sludge, oil refuse, crude oil, fuel oil, heavy diesel oil, lubricating oils, hydraulic fluids, and any mixtures containing these; known carcinogens, mutagens, or teratogens, or materials suspected to be such by responsible scientific opinion" (MPRSA 1972, §227). The tiered tests from the Green Book are the tests to determine "trace" concentrations. These prohibited substances are consistent with the London Convention, an international marine pollution prevention convention.

The London Convention (LC) (IMO 1972), also known as the London Dumping Convention, is the global international instrument for the prevention of marine pollution where ocean dumping of wastes is concerned. The international signatories of the LC include at least 64 countries, of which the U.S. is an active member and a contracting party. The LC, Annex I, lists the substances which are **prohibited** for dumping at sea (the "black list"); and Annex II (the "grey list"), a list of substances that might be disposed of after a special permit is issued by the EPA. Additionally, the MPRSA implements the standards and criteria of the London Convention (IMO 72) [Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, December 29, 1972 (26 UST 2403:TIAS 8165)].

Applicable regulations for a source-to-abyssal seafloor disposal site management strategy, additional to the ones already mentioned, are given within the "*Systems Requirements Report for Abyssal Plains Waste Isolation Project*," prepared for this project by Oceaneering Technologies, Inc. (Marcy et al. 1994). One is referred to the foldout flow chart within the Marcy report for a guide to waste management decision-making processes through the regulatory maze consisting of no less than 69 potentially applicable regulations. The regulations pertain to handling, transportation, and emplacement, and allow for the waste materials to be either nonhazardous or hazardous with respect to the handling and transportation aspects of the waste management scenario.

1.3 Waste Stream Analysis *by William B. Sawyer*

1.3.1 Introduction

The Naval Research Laboratory was tasked with assessing the feasibility of isolating dredged material, sewage sludge, and the fly ash portion of municipal combustor ash on the abyssal seafloor. It is important to note that, of the waste stream types considered by this project, at present only dredged materials may be permitted to be disposed of in the coastal and ocean waters of the U.S. at designated sites. This disposal practice falls under the auspices of the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency as discussed in the previous section.

For clarification the following definitions are used in this report:

(1) Dredged material is "... material excavated from waters of the U.S. or ocean waters. The term dredged materials refers to material which has been dredged from a water body, while the term sediment refers to material in a water body prior to the dredging process" (EPA 1992a).

(2) Sediment is defined as "...material such as sand, silt, or clay suspended in or settled on the bottom of a water body. Sediment input to a body of water comes from natural sources, such as erosion of soils and weathering of rock, or as a result of anthropogenic activities, such as forest or agricultural practices, or construction activities" (EPA 1992a).

(3) Sewage sludge is "...solid, semisolid, or liquid residue generated during the treatment of domestic sewage in a treatment works. Sewage sludge includes, but is not limited to, domestic septage; scum or solids removed in primary, secondary, or advanced waste water treatment processes; and any material derived from sewage sludge. Sewage sludge does not include ash generated during the firing of sewage sludge in a sewage sludge incinerator or grit and screenings generated during preliminary treatment of domestic sewage in treatment works" (EPA 1993a). With increasing demand for processing to higher treatment levels and the promotion of beneficial reuse management strategies for these higher quality sludges, the term "biosolid" has been officially adopted by the Water Environment Federation to mean a dewatered municipal sewage sludge which can be utilized, for example, as fertilizer (WEF 1994).

(4) Fly ash from municipal solid waste (MSW) refers to that component of the MSW incineration product collected within the air pollution cleaning system of the incineration facility. Fly ash so defined "...includes boiler tube or economizer ash (i.e., residue built up on heat transfer surfaces), fly ash (i.e., finer, lighter particulate matter carried by the flue gas), plus scrubber residue (i.e., reaction products formed by the addition of an alkaline reagent, typically lime" (Goodwin 1993). The total product of MSW incineration is termed "combustor ash" and includes, in addition to the fly ash, "...the bottom ash which includes the riddlings or siftings (i.e., material which falls through..." the grates of "...the boiler/ incinerator) plus grate ash (i.e., material which remains on the grate at the discharge end)" (Goodwin 1993). It is the fly ash component of the MSW incineration product that contains the higher proportion of leachable contaminants: in general, the bottom ash component will pass EPA leachate tests, whereas fly ash alone will not pass. Fly ash combined with the bottom ash in produced proportions generally will pass present leachate tests, although increasingly stringent regulations are expected to require treatment of the fly ash by its merits, whether separated or combined (Roethel 1994). Because multiple beneficial uses can be found for bottom ash, this project has not included bottom ash in the project list of materials considered for isolation on the abyssal seafloor; only the fly ash component is considered here.

1.3.2 Volumes and Geographic Distribution

1.3.2.1 Dredged Material

Approximately 306×10^6 m^3 (400×10^6 yd^3) of dredged material are disposed of annually in the U.S. (EPA 1994), of which 45.3×10^6 m^3 (59.2×10^6 yd^3) are ocean-disposed (16-year average, Wright et al. 1993) at 109 ocean sites in U.S. coastal waters. These ocean-disposed quantities reflect the dredged material which the COE, by its charter, must manage in order to "maintain, improve, and extend" navigable waterways. The volumes of dredged material which are ocean disposed do not include material disposed of in estuaries, such as Puget Sound, San Francisco Bay, Chesapeake Bay, and Long Island, or material reutilized beneficially (Wright et al. 1993). It has been estimated by EPA that no more than ~1–3%, or $2\text{–}9 \times 10^6$ m^3 ($3\text{–}12 \times 10^6$ yd^3) of the national total dredged material (total ~300×10^6 m^3) is sufficiently contaminated to require added measures for their disposal (EPA 1994). The COE estimate for volume of dredged material from **navigation maintenance** dredging requiring special handling is about 5%, indicating that the greater proportion of contamination is found in the navigable waterways as opposed to other dredging, or possibly reflecting uncertainty in the volume estimates.

The proportion of contaminated material also varies markedly from location to location: for the COE New York District, 60–75% of the navigation dredged material falls into Categories II and III, either requiring isolation or totally unacceptable for ocean disposal (Greges 1994).

Most dredged material can be disposed at designated sites without special management actions, while some material does require special management. In cases where testing protocols indicate that water column or benthic effects will be unacceptable when conventional

open-water disposal techniques are used, special management action is considered. Testing protocols for dredged material are discussed in Section 1.2, **Environmental Regulations**.

For those cases where disposal practices meet the exclusionary criteria set forth in 40 CFR 220-228, i.e., the dredged material does not exhibit characteristics which would have an adverse environmental impact, those materials would not require testing and could be disposed of at a designated disposal site. For the time period 1988 to 1991, approximately 25% of ocean-disposed dredged material met the exclusionary criteria (Wright et al. 1993). Additionally, seasonal restrictions may be required at a designated site where certain marine resources would be impacted by disposal operations.

The annual average (from 1987 to 1991) geographic distribution, by COE District (plotted at District Headquarters), of ocean-disposed dredged materials is shown in Figure 1.3-1 (Lutz 1994). Twenty-five percent of the dredged material met the exclusionary criteria, while the remainder was tested and found acceptable for open-water disposal.

1.3.2.2 Sewage Sludge

The quantity of sewage sludge generated is directly correlative to population: on a per capita basis, approximately 21 kg (47 lb) of dry material is generated per person per annum (EPA 1993a). Estimates of sewage sludge generation vary depending on how one determines the production. The EPA states that more than 7×10^6 dry metric tons (DMT) of municipal sewage sludge is generated in the U.S. annually. Of this quantity more than 5×10^6 DMT is either beneficially used or disposed of from nearly 13,000 public owned treatment works (POTWs). These POTWs serve more than 70% of the population in the U.S. (EPA 1992b). From the 1990 census, 248.7×10^6 persons live in the U.S., and, if ~71% are served by POTWs, the volume of sewage sludge generated and treated would be approximately 3.8×10^6 dry metric tons based on the EPA value of 47 lbs/person/year of sewage sludge production. The population density distribution for the U.S. and the correlative sewage sludge volume density are shown in Figure 1.3-2.

1.3.2.3 Municipal Solid Waste (MSW) Combustor Fly Ash:

In 1990, 178×10^6 metric tons of MSW was generated in the U.S. (on a per capita basis, 2.0 kg/person/day (4.3 lbs/person/day) is estimated to be generated) (OECD 1993; Berenyi and Gould 1993). The total volume of MSW generated in the U.S. and the proportion which is incinerated is shown in Figure 1.3-3. Of this annual total, 28.9×10^6 metric tons (~16% of total MSW) (OECD 1993) was incinerated in 145 existing waste-to-energy (WTE) incinerators (Berenyi and Gould 1993). Berenyi and Gould state that the 16% value is expected to rise to ~20% when certain advanced planned projects (26 plants) come on line in the near future. These WTE incinerators comprise the majority of combustor facilities in the U.S. Generally, 20–35% of the MSW which is incinerated remains as an ash residue in the form of siftings and grate ash (bottom ash) and fly ash and scrubber residue. The fly ash and scrubber residue collect in the air pollution cleaning system during combustion. Most of the residue which remains following incineration is bottom ash (75–85%), 15–25% remains as fly ash (Goodwin 1993). Ash residues are commonly disposed of in

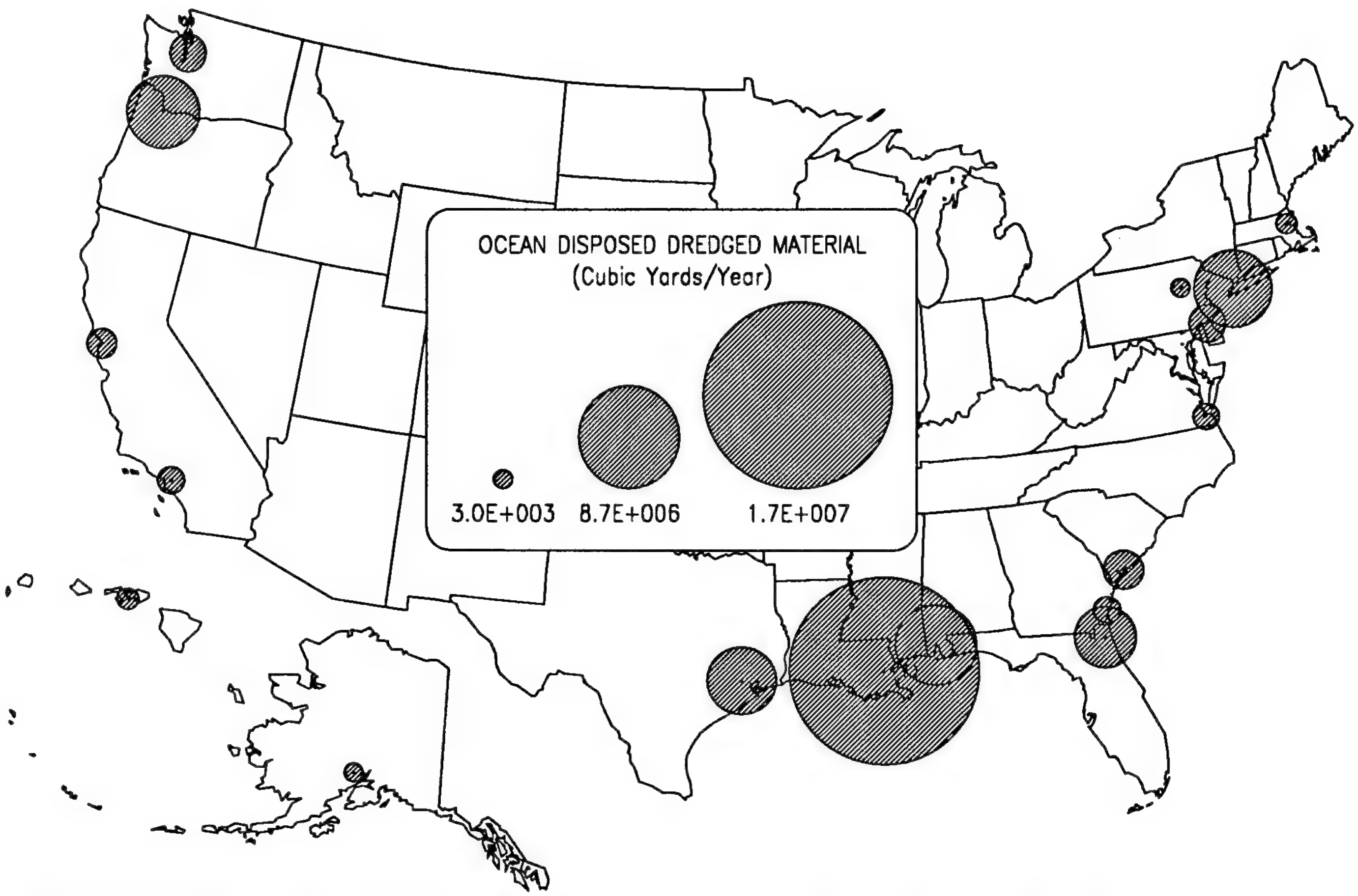

Figure 1.3-1. Geographic distribution of ocean disposed dredged materials plotted at COE District Offices. (Lutz 1994)

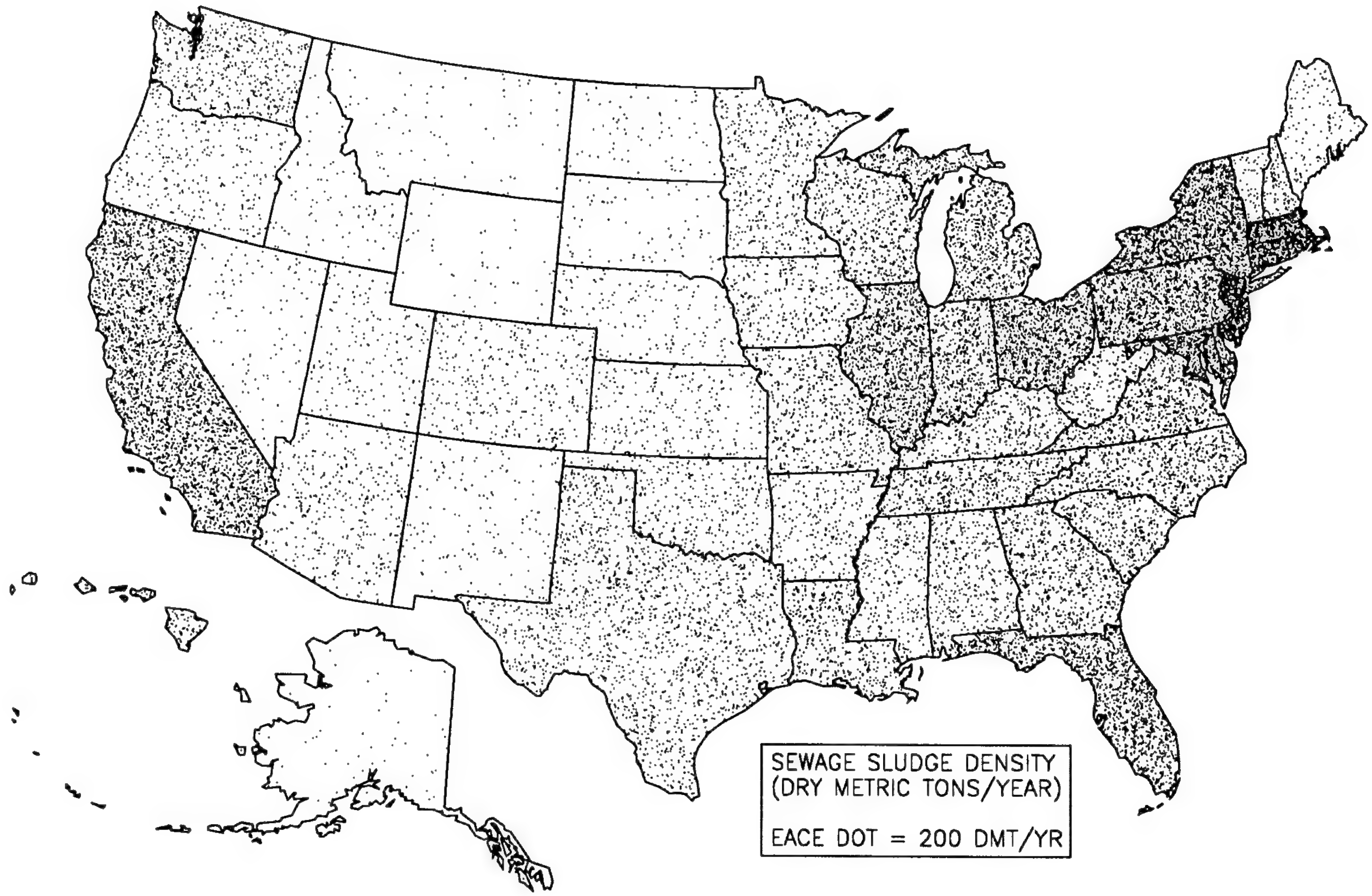

Figure 1.3-2. Sewage sludge density map based on the generation of 47 lbs dry weight per person per year and the 1990 census data. (USDOC 1992; and EPA 1992b).

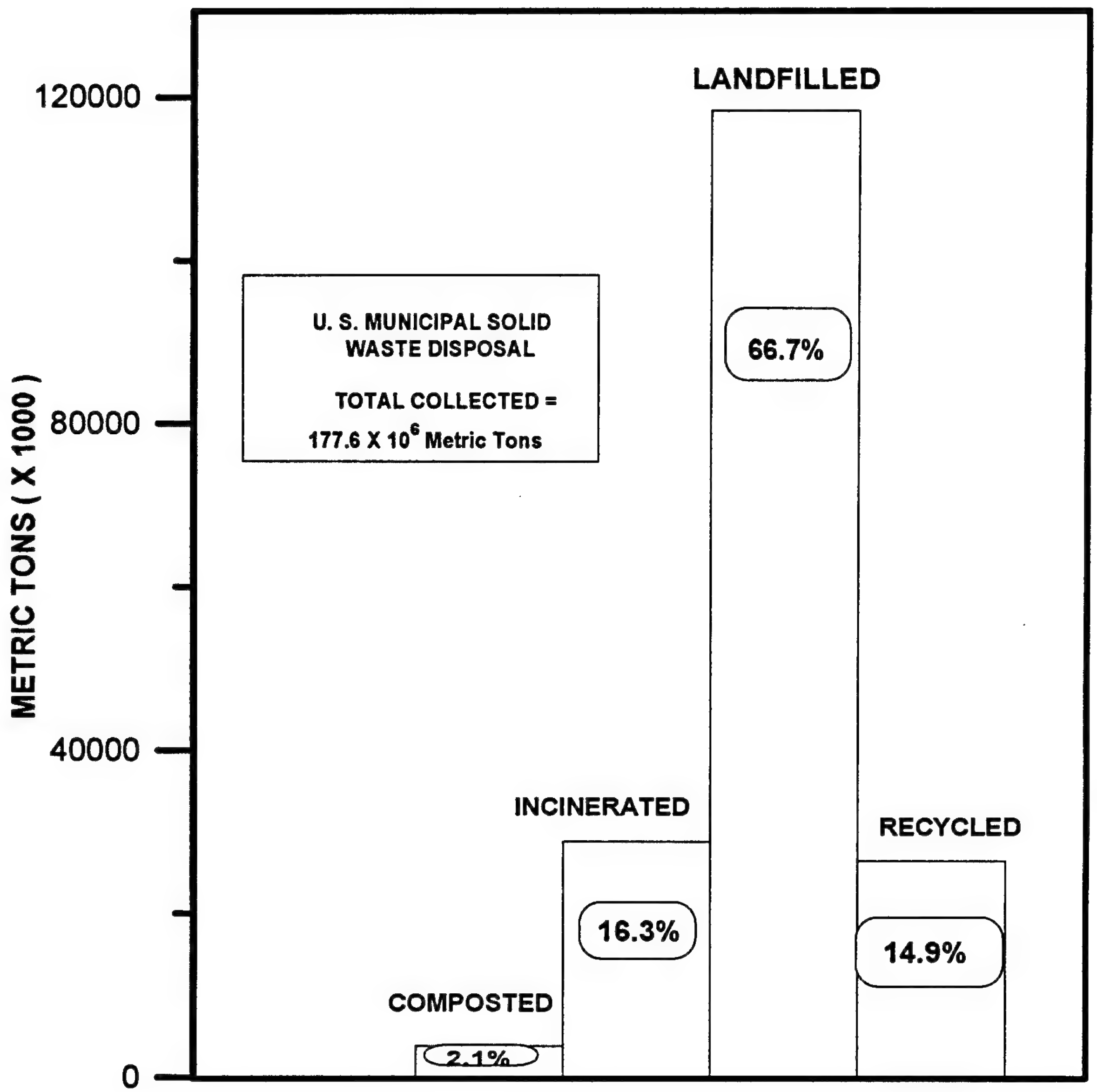

Figure 1.3-3. Total municipal solid waste generation in the U. S.,(1990) (OECD 1993)

landfills (Berenyi and Gould 1993); the fly ash portion contains the greater concentration of contaminants and increasingly must be placed in hazardous waste landfills.

The geographic distribution of WTE incinerators in the continental U.S. and the combustor fly ash volumes are shown in Figure 1.3-4. According to the *Resource Recovery Yearbook* for 1993–1994, 37.4% of the combustor facilities are located in the northeast, 30.4% in the south, 20.5% in the north central, and 11.7% in the west census regions (Berenyi and Gould 1993). These 171 advanced planned and existing projects are located in 37 states shown in Figure 1.3-4.

1.3.3 Physical and Chemical Characteristics

General physical and chemical characteristics for the waste stream materials are presented within "*Systems Requirements Report for Abyssal Plains Waste Isolation Project*," prepared for this project by Oceaneering Technologies, Inc. (Marcy et al. 1994). (See Table 1.4.1-1 of this report for summary of properties.)

1.3.3.1 Dredged Material

Dredged material range in particle size from coarse-grained sediments, such as clean sands used for beach restoration, to fine-grained silts and clays found in estuaries, lakes, and rivers in the U.S. The grain size of these sediments varies considerably from clay-sized particles (<3.9 μm) to coarse-grained sediments, e.g., sands (62.5–2000 μm) and gravels (>2000 μm). Admixtures of all these size classes are common in estuarine, coastal, and ocean waters. Contaminants are normally associated with the finer-grained sediments, i.e., silts and clays, due to fine particle physicochemical reactivity and very large, adsorptive surface areas inherent in the clay minerals. Another important physical property of these sediments is water content. Water content, along with the grain size distribution, plays an important role in both the amount and rate at which available pollutants may sorb to sediments (Cullinane et al. 1990). Bulk density for these materials varies depending on the mineralogical composition (specific gravity of the sediment grains), water content, and grain size distribution. A density value of 1.65 Mg/m^3, with 40% solids, is used for this project.

In preliminary assessment for the National Sediment Inventory database, a number of "hot spots" were identified by the EPA. These studies have identified the coastal areas of Puget Sound, Corpus Christi Harbor, New York Harbor, Baltimore Harbor, Boston Harbor, New Bedford Harbor, Black Rock Harbor, the California sewage outfalls at Palos Verdes, and parts of San Francisco Bay as containing concentrations of chemicals which are potentially detrimental to the environment (NRC 1989). Other studies conducted by Battelle for the EPA cited "... hundreds of sites in the U.S. with in-place pollutants at concentration levels that are of concern to environmental scientists and managers. More than one-third (63 out of at least 184 sites) involve marine or estuarine waterways" (NRC 1989).

Additional site-specific studies (e.g., Squibb et al. 1991) discuss, map, and quantify the toxins in estuarine sediments in New York and New Jersey. The severity of the problem in

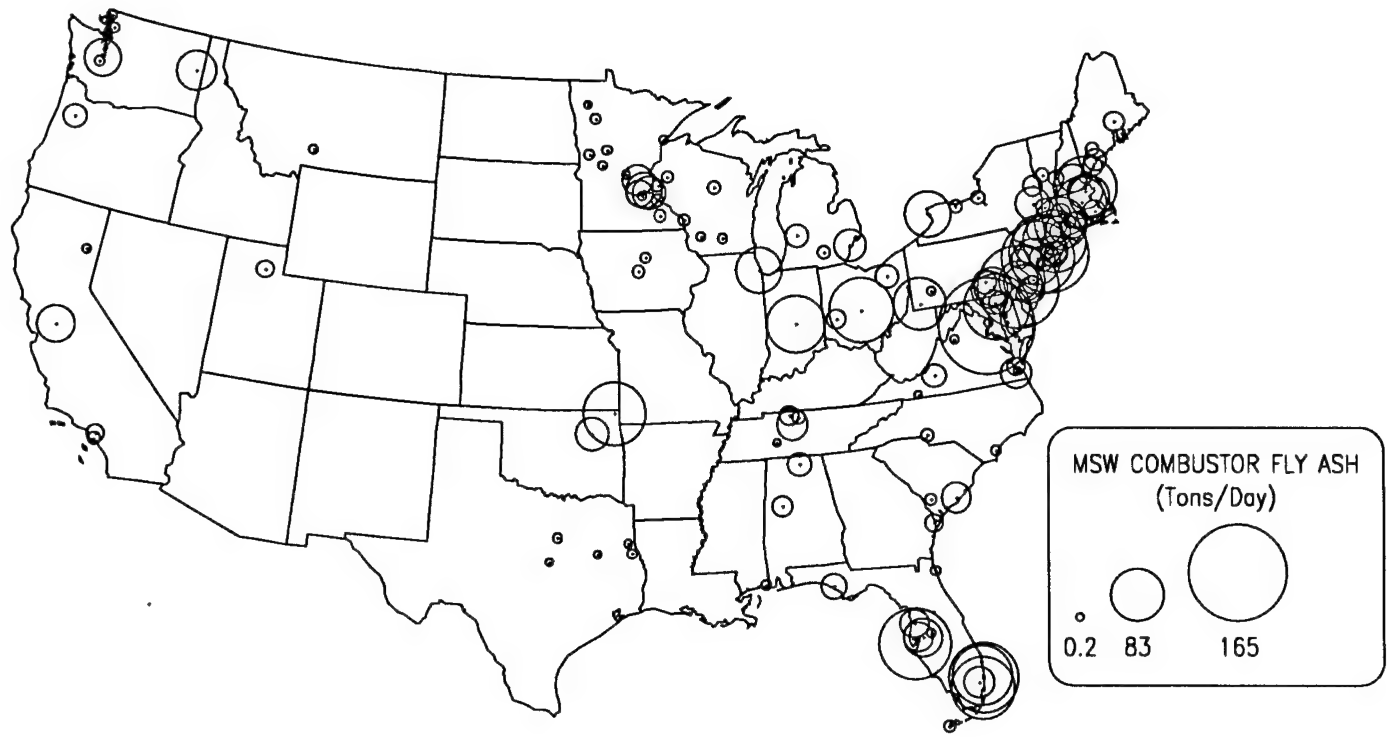

Figure 1.3-4. Geographic distribution of waste-to-energy incinerators (Derived from data in Berenyi and Gould 1993)

the Port of New York/New Jersey has been addressed in a statement by the Hon. Robert Menendez before the Subcommittee on Oversight and Investigations of the Committee on Public Works and Transportation (Menendez 1994). One of the principal contaminants of concern at this port is dioxin.

Issues dealing with contaminated sediments in U.S. coastal areas and their relationship to the dredging of navigable waterways pose perplexing problems in relation to the extent of contamination and volume estimates. The COE estimates that special handling of dredged material due to sediment contamination accounts for only a small portion (about 5%) of the total sediment removed for the purpose of navigational maintenance dredging. The EPA in it's Contaminated Sediment Management Strategy Guidance Document, 1994, states that the National Sediment Inventory "...will be utilized to identify sites where dredged material may be contaminated" (EPA 1994, p vii).

1.3.3.2 Sewage Sludge

The physical and chemical properties of sewage sludge also vary considerably and depend on many factors, e.g., level of treatment, whether the municipal wastewater and storm sewers are combined, and whether domestic wastewater and industrial wastewater are combined. Municipal wastewater facilities treat wastewater to one or more levels of treatment, i.e., either primary, secondary, or tertiary. Primary treatment consists of gravity settling of solids in the wastewater, secondary treatment is a biological process, and tertiary treatment consists of nutrient removal via processes such as chemical precipitation and filtration. Most treatment works in the U.S. treat wastewater through at least secondary level. Each increasing level of treatment provides greater levels of effluent quality and increased amounts of sludge being generated (EPA 1993a).

The corresponding percent solids and levels of organic materials resulting from these levels of treatment are: 3–7% solids and 60–80% organic matter for primary, 0.5–2% solids and 50–60% organics for secondary, and 0.2–1.5% solids and 35–50% organics for tertiary treatment levels. A typical sewage sludge contains ~97% water and dissolved substances and 3% solids. Substances in sewage sludge include items such as: nutrients; metals and organic compounds; and pathogens such as bacteria, viruses, protozoa, and eggs from parasitic worms (EPA 1993a). Centrifugation, belt-presses, and evaporation are methods which reduce the volume of sludges and yield levels up to 20% solids and greater. The 20% solids for sewage sludge is assumed for this abyssal seafloor waste isolation project.

Particle size distributions for digested sewage sludge have been previously determined (Faisst 1980); however, results from this analysis varied with treatment levels, and whether wastewater and storm sewer runoff are combined. Particle size distributions vary with location (see Table 1.3-1) (Lavelle et al. 1988) with the higher proportion of coarse fraction at Owl's Head likely due to inclusion of storm sewer runoff. In the Faisst study samples of digested sewage sludge from Los Angeles were analyzed. The majority of the particles were less than 5 μm as determined by Coulter Counter©, an electronic particle analyzer. Densities range from 0.95 to 1.2 Mg/m^3: the 1.2 Mg/m^3 density value is for sewage sludge cake with up to 50% solids, and the 0.95 Mg/m^3 is for raw sludge (Marcy et al. 1994).

Table 1.3-1. Size fraction distribution for sewage sludge from four municipal treatment plants

Plant	Solids by Weight, %	Size Fraction % >250 μm	250–126 μm	125–64 μm	<64 μm
West Point, Seattle	2.76	5.8	4.7	8.4	81.1
Hyperion, Los Angeles	0.94	5.6	4.8	5.3	84.2
Middlesex, NJ	2.71	7.9	2.3	4.4	85.4
Owl's Head, NY	6.65	42.7	2.65	1.95	52.7

1.3.3.3 Municipal Solid Waste Combustor Fly Ash

The chemical properties of MSW fly ash have been characterized in EPA studies, specifically, *Characterization of MWC Ashes and Leachates from MSW Landfills, Monofills, and Co-Disposal Sites* (EPA 1987a through g, 1990). Other studies (Poran and Ahtchi-Ali 1989; Goodwin 1993) have described physical properties and ash management issues with respect to municipal waste combustor ash. Typical fly ash from MSW incineration contains oxides of aluminum, calcium, iron, and silicon, other more toxic heavy metals, and organic compounds such as dioxins and furans (Poran and Ahtchi-Ali 1989).

The density of fly ash varies from 2.2 to 2.8 Mg/m^3, with solids content ranging from 75–85% (15–25% moisture) as the ash exits the incinerator. The moisture content is maintained to prevent fugitive dusting and for other physical and chemical reasons (Goodwin 1993). Typical fly ash is classified as a poorly graded silty-sand with ~80% of the particles greater than 74 μm and a specific gravity of 2.51 (Poran and Ahtchi-Ali 1989).

1.3.4 Proposed Ports and Waste Volumes

The APWI project has identified potential sites on the abyssal seafloor which would best satisfy constraints applied to a site selection process defined in Section 3.3, **Site Selection Model**. This process relies upon the definition of pertinent factors and the realistic weighting of these factors in order to formulate and identify abyssal seafloor areas suitable for waste isolation strategies.

This feasibility study also required identification of large U.S. coastal population centers with adequate port facilities. The ports identified for this analysis are: New York/New Jersey, Miami/Ft. Lauderdale, Galveston/Houston, Los Angeles, and Seattle. Estimates of volumes of waste from these coastal cities and the adjacent areas were further delimited to those wastes generated within a 160-km (100-mile) radius of the ports. Based on these requirements, volume estimates for the dredged material, sewage sludge, and fly ash are shown in Table 1.3-2, and their geographic distribution in Figure 1.3-5 (volume estimates

Table 1.3-2. Annual volumes/mass of waste materials within 160 km (100 statute miles) of port facilities chosen for Abyssal Seafloor Waste Isloation Project. (Berenyi and Gould 1993; Jin et al. 1995; Greges 1994; Hauch 1994; Risko 1994; Kendall 1994)

PORT FACILITY	DREDGED MATERIAL VOLUME (Million m^3) (~40% Solids)	SEWAGE SLUDGE MASS (Million Metric Tons) (20% Solids)	MUNICIPAL COMBUSTOR FLY ASH MASS (Million Metric Tons) (~90% Solids)	TOTAL WASTE MATERIALS BY PORT (Million Metric Tons) (Assuming 1 m^3 = 1.2 metric tons)
NEW YORK/ NEW JERSEY	2.8–3.4	2.4	0.40	6.2–6.9
MIAMI/ FT. LAUDERDALE	0.34	0.4	0.15	1.0
GALVESTON/ HOUSTON	0	0.4	0	0.4
LOS ANGELES	0.21	1.5	0.04	1.8
SEATTLE	0.04	0.4	0.02	0.5
TOTALS BY WASTE TYPE	3.4–4.0	5.1	0.61	9.9–10.6

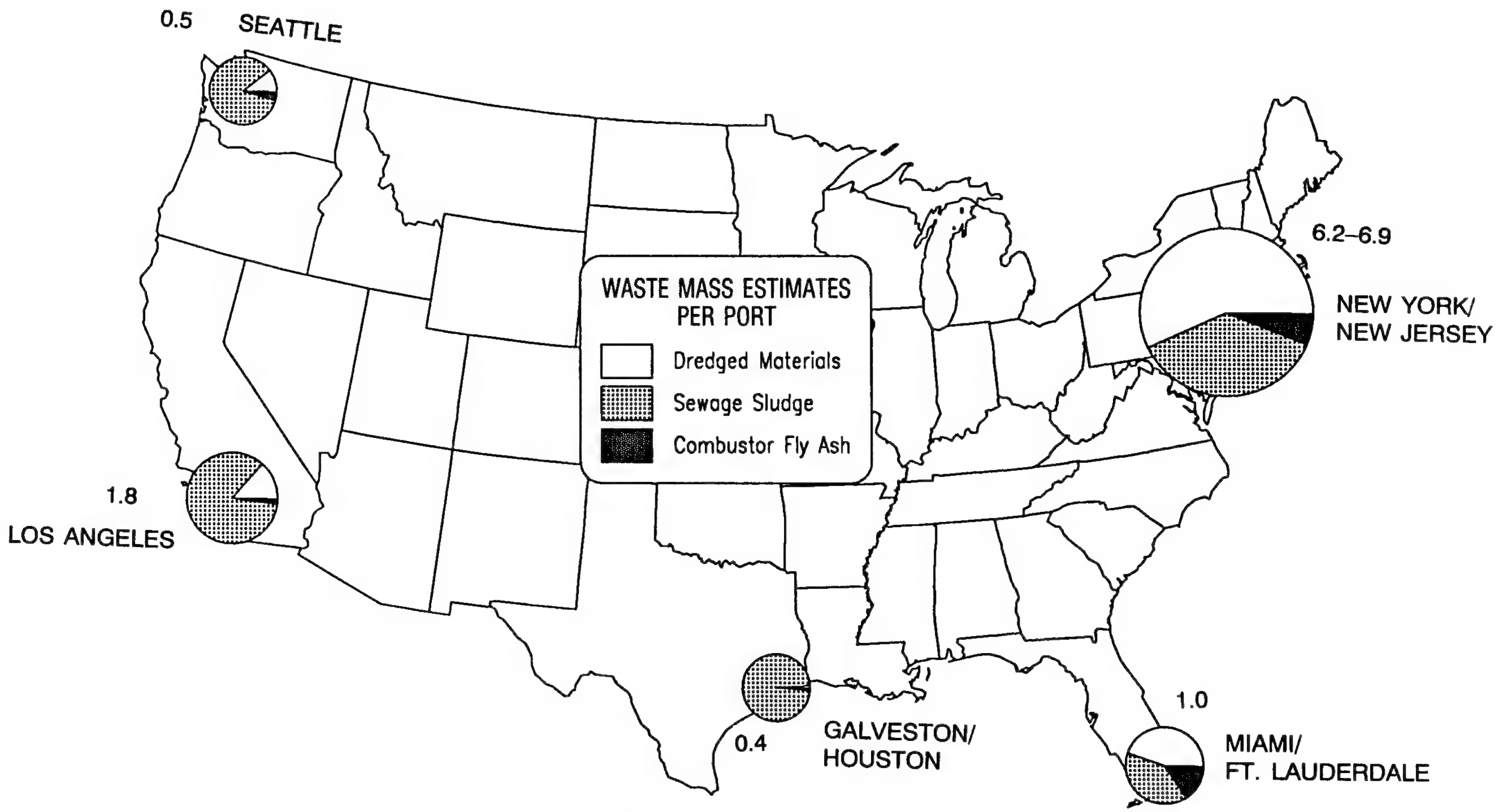

Figure 1.3-5. Estimated mass of waste materials potentially available for Abyssal Seafloor Waste Isolation Project ($\times 10^6$ metric tons).

for sewage sludge and MSW combustor fly ash from the *Economic Analysis Report*, prepared by the Marine Policy Center of the Woods Hole Oceanographic Institution for this project). The largest annual portion of the waste stream available for deep-ocean isolation comes from the New York/New Jersey area with lesser amounts from Los Angeles, Miami/Ft. Lauderdale, Seattle, and Houston.

The volumes cited for each waste stream are the total volumes generated within 160-km radius of the selected ports: the authors assumed here that these total volumes would be available for abyssal seafloor isolation provided the price is competitive with other options. The actual volumes that would be consigned to abyssal seafloor isolation would likely not be as large as those noted in Table 1.3-2. However, we initially assume total availability in order to maximize efficiencies of the APWI concepts, with corrections to our costs for volume reductions to be made later.

Annual volume estimates for sewage sludge and fly ash are based on population statistics and/or published information. These estimates are therefore readily obtained from the literature. However, the estimated volumes of dredged material shown in Table 1.3-2 vary and depend on a number of factors. Wright et al. (1993) point out that factors such as volumes dredged from current Federal projects, number of new permitted private projects and new one-time projects, dredging required due to large depositional events related to storms and/or flooding, and budgetary matters are responsible for large variability in annual volumes. The majority of dredged material disposed in ocean waters is that from Federal Civil Works projects with lesser amounts from permitted projects (Wright et al. 1993).

From personal communication with COE District offices, port authorities, local governments, and environmental agencies from ports identified in this project, best estimates of volumes of dredged material were identified. The volume estimates are limited to those ongoing projects requiring special management actions for dredged material disposal and/or new or proposed projects by COE District Offices where special management action is indicated. Therefore, the annual volume estimates are somewhat hypothetical in that the volumes which are based on ongoing projects **are** actual, whereas dredged material volume estimates from the COE Districts for new projects (in the process of permitting or awaiting other factors) would not be available for disposal until permits are granted and/or disposal options are defined and implemented [e.g., the proposed dredging of the Miami River (GEC 1993) and dredging of the Port of New York/New Jersey (Menendez 1994)].

Since these volumes are estimates of the potential requirement for dredged material disposal from new projects, they should be viewed tentatively and only for ASWI Project illustrative purposes. The dredged material volumes for New York, Los Angeles, and Seattle reported by COE District Offices represent volumes of material that are removed annually which require special management actions [i.e., Houston and Miami generally dispose of dredged materials which do not require special management, except for the proposed Miami River project, a ~2-year dredging effort]. The proposed project for dredging the Miami River is pending local decisions regarding the ultimate disposal site. The annual volume estimates for the Port of New York/New Jersey are thought to be high and may decrease when revised testing procedures are implemented. The volume estimates used for this port are based on that dredged material which is tested and falls in COE Categories 2 or 3. Category 1 materials are those suitable for ocean disposal without special management

actions, while category 2 and 3 materials require special management (EPA Region 2, specific disposal categories) (Greges 1994).

1.4 Abyssal Seafloor Waste Isolation

1.4.1 Engineering Concepts *by Martin G. Fagot and Philip J. Valent,* largely excerpted from reports by Oceaneering Technologies, Inc., and Marine Policy Center, WHOI

1.4.1.1 Background

Approximately 45% of the effort on the Abyssal Plains Waste Isolation Project was directed to the study of technical feasibility, advantages, disadvantages, and economic viability of candidate transport and abyssal seafloor emplacement systems for sewage sludge, fly ash from municipal incinerators, and dredged material. This section provides a review of results of the engineering concepts study to provide necessary background for understanding the approach taken in the environmental assessment, site survey plan, and monitoring plan tasks of this project.

The Technical Assessment Task was divided into three study areas: system level requirements, technical analysis, and cost estimates and comparisons. In this Environmental Assessment Report, system level requirements and technical analysis areas are reviewed in substantial detail, while the cost estimate and comparisons study area is given cursory treatment. More detailed information regarding the Technical Assessment Task study areas is to be found in NRL Contract Reports: (1) system level requirements results in Marcy et al. (1994), (2) technical analysis background, analysis, results, and conclusions in Hightower et al. (1995a), and (3) cost estimates for concept construction and operation in Hightower et al. (1994).

1.4.1.2 System Level Requirements

The system level requirements study was undertaken to identify and document applicable assumptions and requirements used to evaluate and compare potential waste transport and emplacement concepts. Critical requirements and limitations were imposed on concept configurations and design by: (1) the waste stream characteristics, (2) transit distances to the surrogate (or strawman) emplacement sites, (3) environmental conditions in transit to and at the surrogate sites, and (4) system performance and operational requirements.

(1) Waste Stream Characteristics

The waste stream physical and chemical characteristics for sewage sludge, fly ash from municipal incinerators, and dredged material directly and significantly impact design and configuration of the handling, containment, transport, and emplacement concepts. From Table 1.4.1-1, the waste streams are seen to exhibit a wide range of properties, e.g., characteristic bulk specific gravity ranging from 1.04 for sewage sludge at solids content of

Table 1.4.1-1. Waste Stream Physical and Chemical Properties

	Dredged Material	Sewage Sludge	Fly Ash
Bulk Specific Gravity (by weight)	1.25	1.04****	2.04
% Solid Content	32%	20%*	85%
% Volatile Material in Solids	varies	60-80% (raw) 30-60% (digested)	
% Organic	10%	35-80%**	0–15%
% Insoluble in Water		90-95%	99–100%
% Ignition Loss			0.8–16%
Size of Particles	gravel 4.76–76.2 mm sand 0.074–4.76 mm silt 0.005–0.074 mm clay <0.005 mm		0.001–1.0 mm
Composition	sand, silt, & other sediments. (range of contaminants varies w/source)	55% elemental C	50% SiO_2
Energy/Unit Mass		14–28 kJ/g (raw) 7–14 kJ/g (digested)	n/a
pH	n/a	5-8	
Misc		Odor/pathogens, Gas production***	

*The 80% water is internal and absorbed, it is not free-draining

** 35% if digested.

** Gas Analysis Methane 0–75%

**** Sewage Sludge and fly ash or another material can be mixed to obtain a specific gravity of 1.25

20% to 2.04 for fly ash (with a solids content of 85%). The bulk specific gravities correspond to water contents at which these wastes would most likely be transported. This water content provides for minimum cost from the point of pretreatment at the source while maintaining reasonable handling characteristics. Minimum volume is desirable to increase handling and transport efficiency, but the cost of removing the water increases significantly when the dewatering process shifts from mechanical to thermal. Mechanical dewatering of sewage sludge by belt press or centrifuge processes increases the solids content to about 20% (Hightower et al. 1995a). Fly ash waste includes about 15% water (85% solids) as it is produced at municipal waste incinerators. The water is introduced in the flue gas scrubbing process to minimize fugitive dusting during transport and handling (Goodwin 1993, pp 5–6). Dredged material contains an average solids content of 32%.

One significant consideration with isolation of these waste streams in the deep sea is ensuring that the materials remain in place when emplaced on the abyssal seafloor. Dredged material with a bulk specific gravity of 1.25, and certainly the fly ash with bulk specific gravity of 2.04, will stay in place in bulk form. However, the sewage sludge, with bulk specific gravity of 1.04, in seawater with bulk specific gravity of 1.025, is near neutrally buoyant and could be easily moved on the seafloor by even the very slight near-seabed currents expected on the abyssal plains. A possible solution to the problem is to add weighting material to the sewage sludge. At those transport loading points where an adequate fly ash waste stream exists, fly ash of bulk specific gravity of 2.04 could be blended with the sewage sludge to yield a bulk specific gravity of 1.25 or higher.

Another design constraint imposed by the waste stream on the system design is the possible generation of methane gas during transport of sewage sludge or dredged materials with high organic contents. Handling and transport concepts have incorporated venting of these gases into the designs.

(2) Surrogate Sites for Abyssal Seafloor Waste Isolation

Five preliminary sites for abyssal seafloor waste isolation, first termed "Strawman Sites" and later "Surrogate Sites," were selected early in the project to provide an early basis for determining quantitative parameters required for execution of the engineering analysis. The locations of these Surrogate Sites are given in Figure 1.4.1-1. These five sites were selected using site selection criteria described in Section 3.0, **Site Selection**, using a series of map overlays of the various exclusionary and rating factors to manually identify those most promising sites for waste isolation. Two were selected in the Atlantic, one in the Gulf of Mexico, and two in the Pacific. Table 1.4.1-2 presents transit distances from possible waste-loading ports to these surrogate sites. For the engineering analysis, a mean value of 1230 km (665 nmi) was used as the mean transport distance for east coast ports.

(3) Surrogate Site Environmental Conditions

Environmental conditions at the surrogate sites, especially estimated sea states, are critical input data for developing the emplacement concepts and determining operational availability. Figure 1.4.1-2 presents site operational availability (days) as a function of sea

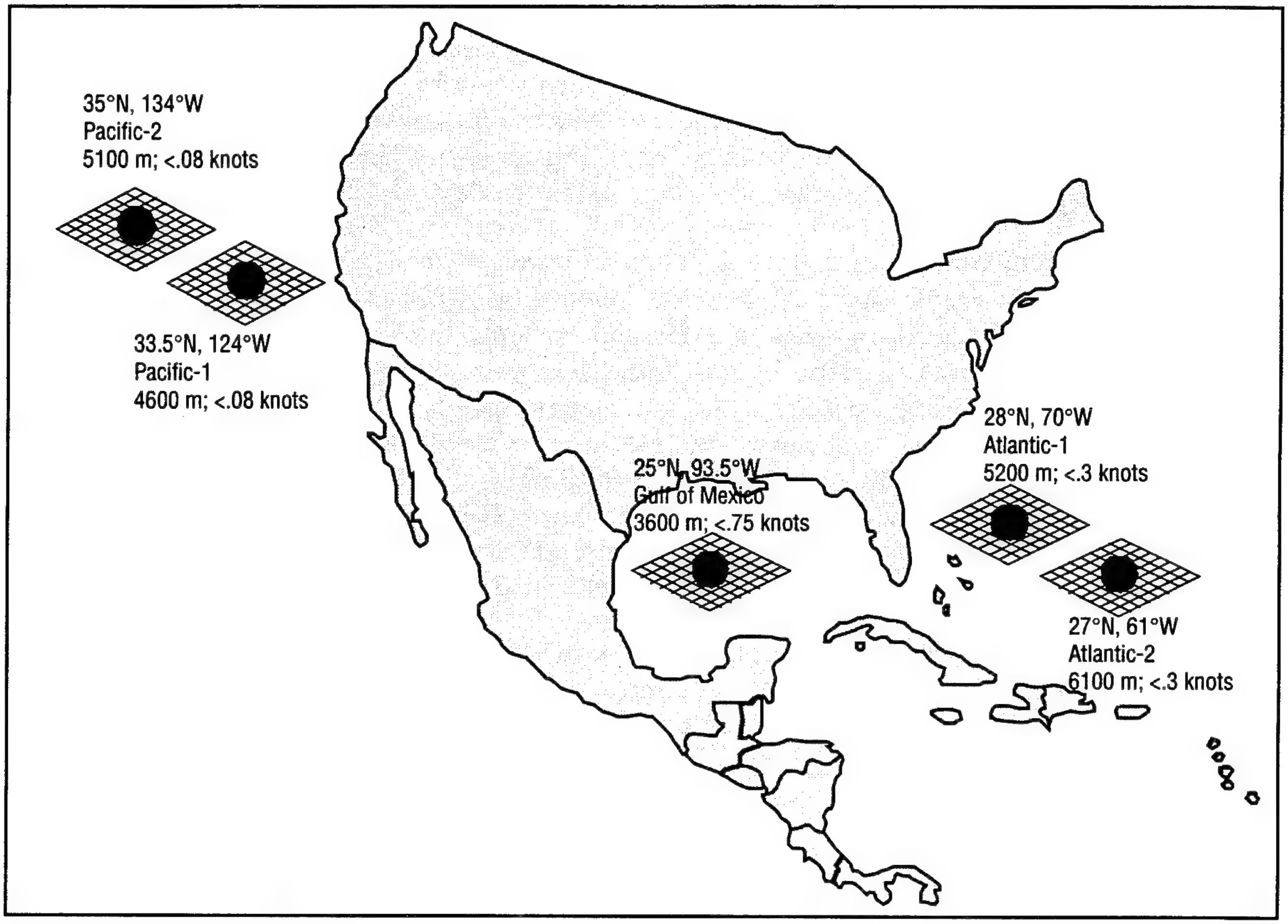

Figure 1.4.1-1. APWI project surrogate site locations.

Table 1.4.1-2 Tabulation of Candidate Port to Surrogate Site Transiting Distances

ATLANTIC SITES

PORT	DISTANCE TO SITE ATLANTIC 1, (28° N,70° W)	ATLANTIC 2, (27° N,61° W)
Boston	1600 km (864 nmi)	1937 km (1046 nmi)
New York	1458 km (787 nmi)	1935 km (1045 nmi)
Philadelphia	1404 km (758 nmi)	1937 km (1046 nmi)
Baltimore	1392 km (752 nmi)	1985 km (1072 nmi)
Norfolk	1159 km (626 nmi)	1817 km (981 nmi)
Wilmington, NC	1025 km (553 nmi)	1806 km (975 nmi)
Charleston	1089 km (588 nmi)	1930 km (1042 nmi)
Savannah	1157 km (625 nmi)	2017 km (1090 nmi)
Jacksonville	1158 km (625.nmi)	2043 km (1103 nmi)
Port Canaveral	1037 km (560 nmi)	1931 km (1042 nmi)
Miami	1038 km (561 nmi)	1912 km (1032 nmi)
Mean Distances	1229 km (664 nmi)	1932 km (1043 nmi)

GULF OF MEXICO SITE

PORT	DISTANCE TO SITE 25° N,93.5° W
Tampa	1146 km (619 nmi)
Gulfport	736 km (398 nmi)
Galveston	495 km (495 nmi)
Brownsville	405 km (219 nmi)
Mean Distances	696 km (376 nmi)

PACIFIC SITES

PORT	DISTANCE TO SITE PACIFIC 1, 33.5° N,124° W	PACIFIC 2, 35° N,134° W
Anchorage	3593 km (1939 nmi)	3124 km (1687 nmi)
Valdez	3463 km (1870 nmi)	3033 km (1638 nmi)
Kodiak	3444 km (1854 nmi)	1876 km (1553 nmi)
Port Angeles	1626 km (878 nmi)	1700 km (918 nmi)
Seattle	1577 km (851 nmi)	1704 km (920 nmi)
Vancouver	1353 km (730 nmi)	1519 km (820 nmi)
Portland	1346 km (726 nmi)	1511 km (815 nmi)
San Francisco	499 km (270 nmi)	583 km (1081 nmi)
Port Hueneme	447 km (241 nmi)	1354 km (731 nmi)
Los Angeles	531 km (286 nmi)	1448 km (782 nmi)
San Diego	636 km (343 nmi)	1565 km (845 nmi)
Mean Distances	1002 km (541 nmi)	802 km (1485 nmi)

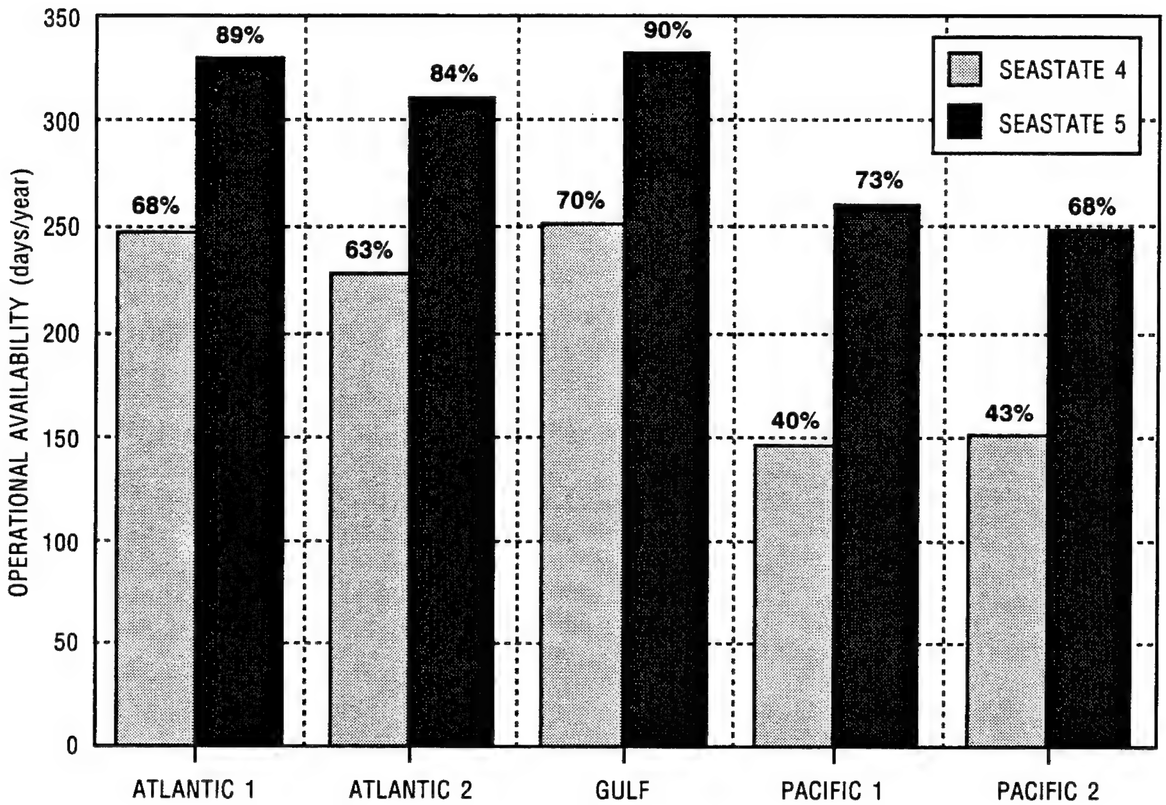

Figure 1.4.1-2. APWI project surrogate sites—operational availability vs. seastate.

state for the five surrogate sites. If we average expected availability at all five sites, and if the emplacement concept platform were designed to operate in sea-state five, then the concept would be able to operate 80% of the time; for all five sites and designed for sea-state four, the concept would be functional only 57% of the time. Sea-state five was chosen as the design upper limit for platform operation to bring operational availability up to near 80%, thus improving economic viability of the concept, and because sea-state five is a standard for many open-ocean operations. The concepts were designed to weather sea-state eight conditions to ensure no loss of equipment critical to survival.

Emplacement concept design and expected performance depend strongly on the water current speed profiles at the sites. The current profile versus depth adopted for this engineering analysis (Fig. 1.4.1-3) summarizes the worst-case envelope of maximum expected currents at any location worldwide, and includes estimates of near-seafloor current speeds at each of the five surrogate sites (Eastport 1986).

The maximum expected operating water depth is another critical parameter for the emplacement concept design. Water depth at the deepest surrogate site, Atlantic-2, is 6100 m: a 10% margin was added to this depth figure for design and costing, resulting in a concept design water depth requirement of 6700 m.

(4) Concept Performance/Operational Requirements

A summary of performance/operational requirements reviewed above combined with additional general requirements imposed on the prospective emplacement concepts and operations is presented in Table 1.4.1-3. The rationale for the requirements of Table 1.4.1-3 are found in Marcy et al. (1994) and Hightower et al. (1995a).

1.4.1.3 Emplacement Concepts Review

(1) **Surface Emplacement**: The Surface Emplacement concept (Fig. 1.4.1-4) envisions either a self-powered bulk carrier or an integrated tug/barge (ITB) transporter with its cargo hold divided into 51 separate cells. Each cell carries about 380 m^3 of waste material enclosed in a disposable, polyester fabric, bag-like container, yielding a total cargo capacity of 26,000 m^3 (34,000 yd^3). The waste material is loaded into the individual bag-lined, free-flooding cells and the bags closed in port. The transporter then transits to the waste isolation site and releases the bags of waste through trap doors forming the bottom of each cell. The cells are emptied at intervals over a range of 0.5- to 3.0-hr periods depending on time required for pumping of water to adjust ballast. The location of bag release at the ocean surface can be adjusted to account for horizontal deviation of the bag fall path due to the water currents encountered. Initially the project team set a goal to hold the waste placement to within a 500-m × 500-m area on the seafloor to minimize that area of the seafloor being impacted and to make the task of subsequent monitoring easier. The goal of emplacing the bags of waste within a box 500 m on a side is achievable provided that the bags free-fall stably. The bag design required to ensure hydrodynamic stability during free-fall requires investigation and definition, but stability is expected to be achievable with reasonable bag designs (shapes). Concept evaluation shows the ITB transporter is preferred

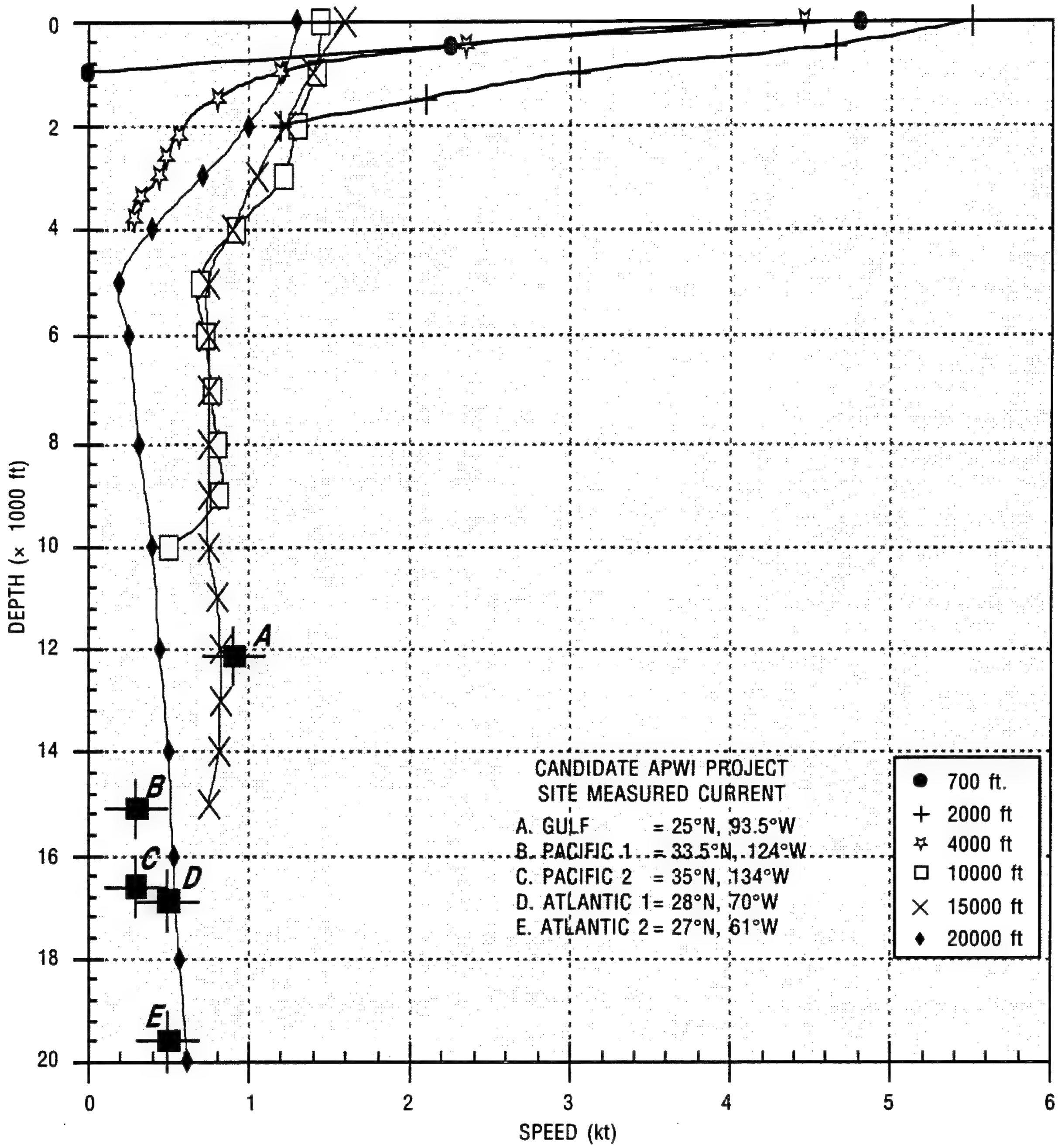

Figure 1.4.1-3. Maximum current profile vs. seafloor depth (derived from Specification 3100, CURV III System (Eastport 1986)).

Table 1.4.1-3. System Performance/Operational Requirements

1. System Capability:
   a. 2.5 million metric tons/yr/port
   b. Maximum transiting distance to Atlantic, Gulf, or Pacific APWI sites from any coastal port <1852 km (1000 nmi)
   c. No exposure of waste stream products to intervening water column, including leakage and spill prevention design features
   d. Static electricity dissipation design features
   e. Validation and verification design features
   f. Range safety design features: Tracking system to allow minimum of 1,000 m standoff between surfacing submersible and host platform.

2. Transiting speed: 6.2 m/s (12 knots), minimum

3. Operational depth: 6700 m, maximum

4. Emplacement accuracy: within 500 m × 500 m box

5. Reliability: MTBF > 700 hrs.

6. Maintainability: MTTR < 80 hrs.

7. Environmental:
   a. Operational: Sea state 5 conditions
   b. Survivability: Sea state 8 conditions
   c. Currents: <0.78 m/s (1.50 knots) on surface; <0.39 m/s (0.75 knots) on Abyssal Seafloor
   d. Hydrostatic pressure: <62 MPa (9000 psig)
   e. Temperature: 0° C to 49° C

8. Waste Stream Compatibility: (Non-Hazardous)
   a. Contaminated dredged materials: 32% solids by weight
   b. Sewage sludge: 20% solids by weight
   c. Municipal incinerator fly ash: 85% solids by weight

9. Design Requirements:
   a. American Bureau of Shipping
   b. Code of Federal Regulations 33, 40, 46 & 49 CFR
   c. Safety of Life At Sea (SOLAS)
   d. American Petroleum Institute API RP 2A
   e. Interface Std. for Shipboard Equipment, DOD STD-1399

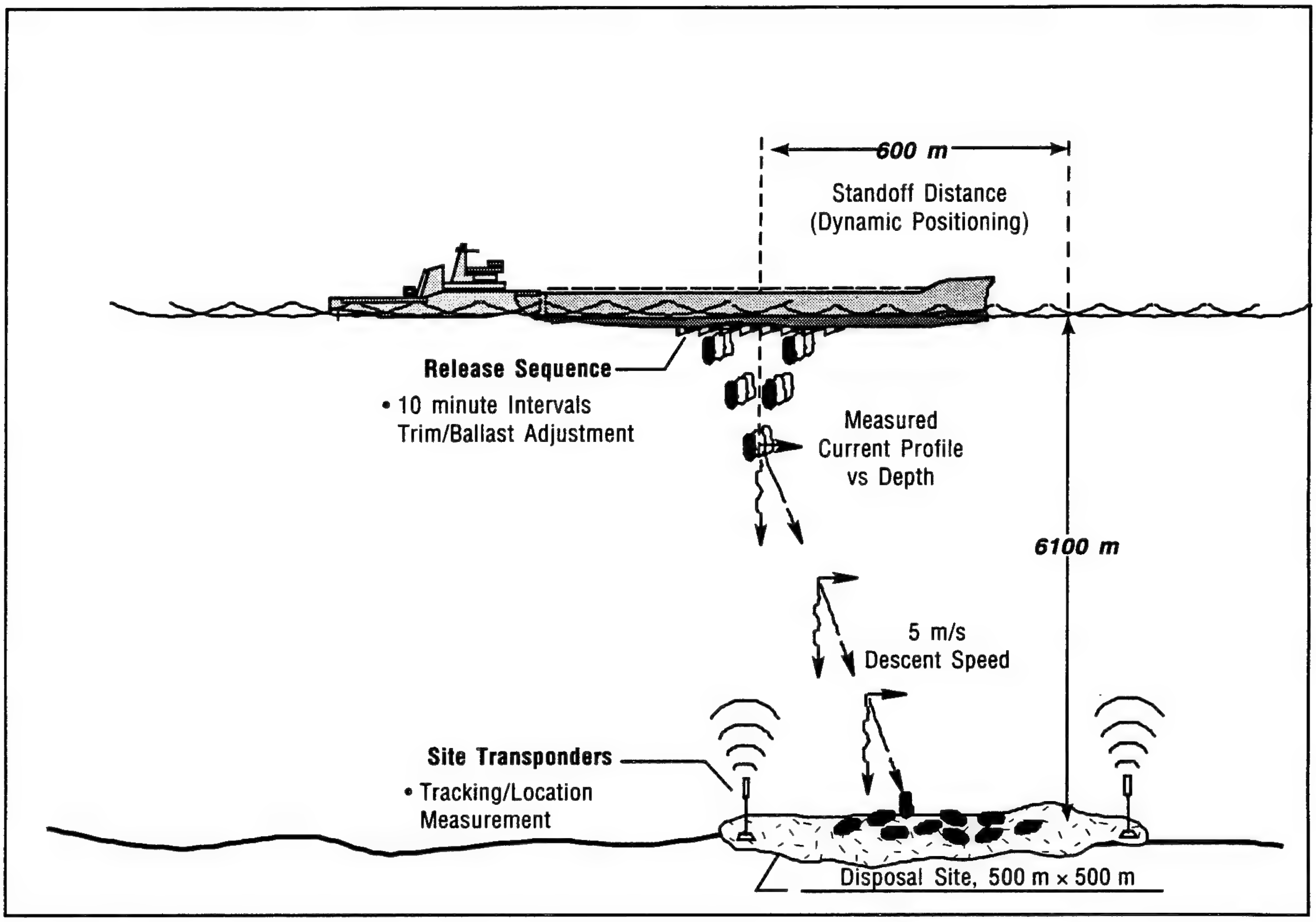

Figure 1.4.1-4. Surface Emplacement Concept uses 50 ea. 382 m^3 capacity geotextile bags for deposit of 25,000 metric tons bulk waste into 500 m x 500 m monitored APWI project isolation sites.

over the self-powered bulk carrier because the ITB is operationally simpler and involves fewer and simpler regulatory and manning issues (Hightower et al. 1995a).

A critical component of the surface emplacement concept is the use of the disposable, high-density (heavier-than-seawater), fabric bags to contain the waste material when exiting the transporter cells and during free-fall to the seafloor. The use of such bags, using clean sand filler, was pioneered by the Dutch for controlled placement and retention of underwater construction for flood protection (Ockels 1991; Jagt 1988). The U.S. Army Corps of Engineers has applied similar fabric bag construction, termed "geosynthetic bags," for containing clean sand for construction of underwater groins for channel control in the Mississippi River near Baton Rouge, LA. The COE has used large, geosynthetic fabric tubes for containing contaminated fine-grained dredged material in Mobile Bay, AL, and has used geosynthetic bags for containment of lightly contaminated dredged material near Marina del Ray, CA, in November-December 1994 (Fowler 1994). In those instances where bags were used for dredged material emplacement, the free-fall distance did not exceed 30 m. The performance of the bags over these short free-fall distances is of direct application to abyssal seafloor depths because the waste-filled bags reach terminal velocity within a fall distance of 1–2 bag diameters, or about 4–8 m (Fowler 1994). When used to contain contaminated dredged materials (as at Mobile Bay), a double-wall bag construction is employed. The outer, coarse-fibered material provides the required tensile strength, and an inner, fine-pored construction serves as a filter to retain the very finest particulate matter (and sediment contaminants which are normally found adsorbed on that fine particulate matter), while allowing relatively clean excess water to exit the bag. Containment of fine material and adsorbed contaminants in the fabric bag during transport, release from the transporter, and fall through the water column appears to be quite feasible and practical. When using the geosynthetic bags for underwater construction, tearing of the bags as they slide out of the partially opened doors of the bottom dump hopper barges and loss of contained dredged material has been experienced. Rupture of the bags during the fall through the water column or rupture on landing on the seafloor has not occurred (Fowler 1994). Development of a highly reliable system for release of the bags from the transporter is not foreseen to be an insurmountable problem; although the writers allow that some low probability of bag tearing/rupture/bag-seam failure does exist and should be factored into assessment of the Surface Emplacement concept.

Rupture of the geosynthetic bags can be limited by filling the bags to only 75% of capacity, thus limiting the "hoop" tensile stresses that develop in the bag wall on leaving the transporter and on impact with the seafloor [the "full" capacity of the bags to be used would be 510 m^3 (670 yd^3), and they would be filled to only 380 m^3 (500 yd^3)]. Rupture of the bags due to impact with the seafloor is limited by the partial filling criteria and also by the "trapped water" effect of that layer of water between the bag and the seafloor serving as a hydrodynamic brake to slow the bag as it approaches the seafloor (Atturio and Valent 1978). As demonstrated by Dutch and COE experience, bags filled to only 75% of capacity will not rupture upon landing on the seafloor. Polyester fabric is projected not to undergo any substantial chemical degradation for a few hundred years in the absence of light at abyssal seafloor temperatures (see Section 1.4.2, **Bag Composition**). Biological degradation due to "fish bite," borers, etc., is intuitively likely, but no data are in hand from which understanding and projections may be developed. The bag filter fabric will allow

passage of water and dissolved materials into and out of the bags, thus allowing access to the contained waste material by indigenous microfauna.

The Surface Emplacement concept has several advantages over the other concepts evaluated:

(a) This concept is technically the simplest solution to emplacement of bagged bulk waste at an abyssal seafloor waste isolation site, thus, it involves the least risk.

(b) Solutions to the design of appropriate platform configurations exist in conventional naval architectural practice.

Disadvantages of the Surface Emplacement concept are:

(a) Because the waste-containing bags must free-fall through the entire water column, concentration of the bag landings within a specified 500-m × 500-m box at 6100-m depth on the seafloor may not be possible. Water velocity profiles can be measured immediately prior to bag release, but slight variations in the bag-contained weight, volume, and assumed shape could cause deviations in predicted bag free-fall velocity and predicted horizontal offsets. Of even greater concern, deviations in distribution of mass within the bags and/or asymmetries of the bags could adversely impact bag hydrodynamic stability and result in horizontal skating/sailing of the bags during free-fall descent.

(b) COE operations show that the highest potential for bag tearing or rupture occurs during release through the bottom dump doors of the hopper barge. Such bag rupture at the ocean surface could release a significant mass of contaminants in the near-surface, euphotic, highly productive zone of the ocean. To prevent such occurrence, a well-engineered bag release system must be developed.

(c) The geosynthetic bags are presently being manufactured in the U.S. by only two vendors, with total annual production only one-seventh of that required to supply the Surface Emplacement concept. Capacity to fabricate the bags should grow quickly to meet demand; however, the capacity to manufacture the polyester fabric in the quality (tensile strengths and filtering capability) and quantities required must be verified.

(2) **Remotely Operating Vehicle (ROV) Glider**: The ROV Glider concept has as its key element an ROV submarine glider designed to negotiate, when fully loaded with waste material and thereby in a net negatively buoyant mode, a stable, 40°-below-horizontal glide path to 200 m above the seafloor (Fig. 1.4.1-5). At 200-m altitude, the ROV Glider begins a sequential release of waste cargo. Release of the waste material alters the ROV Glider buoyancy to net positive, changing the glide path to above horizontal and the ROV Glide returns to the surface. Total time for descent, waste release, and return is estimated at 90 min. The ROV Glider would be transported to the waste isolation site by an integrated tug/barge transporter. The catamaran hull barge would serve as a "garage" for the ROV Glider while transporting the glider at the ocean surface. The cargo hold of the ROV Glider would be configured much like that of the Surface Emplacement transporter, but the cells would be smaller, dictated by the lesser hull depth of the glider, with 153 cells holding 128 m^3 (166 yd^3) of waste in fabric bags totaling 25,000 DWT of waste.

Dynamic directional stability of the ROV Glider is assured, even during the initial stages of the glide, by providing neutral or positive static (weather vane) stability in the

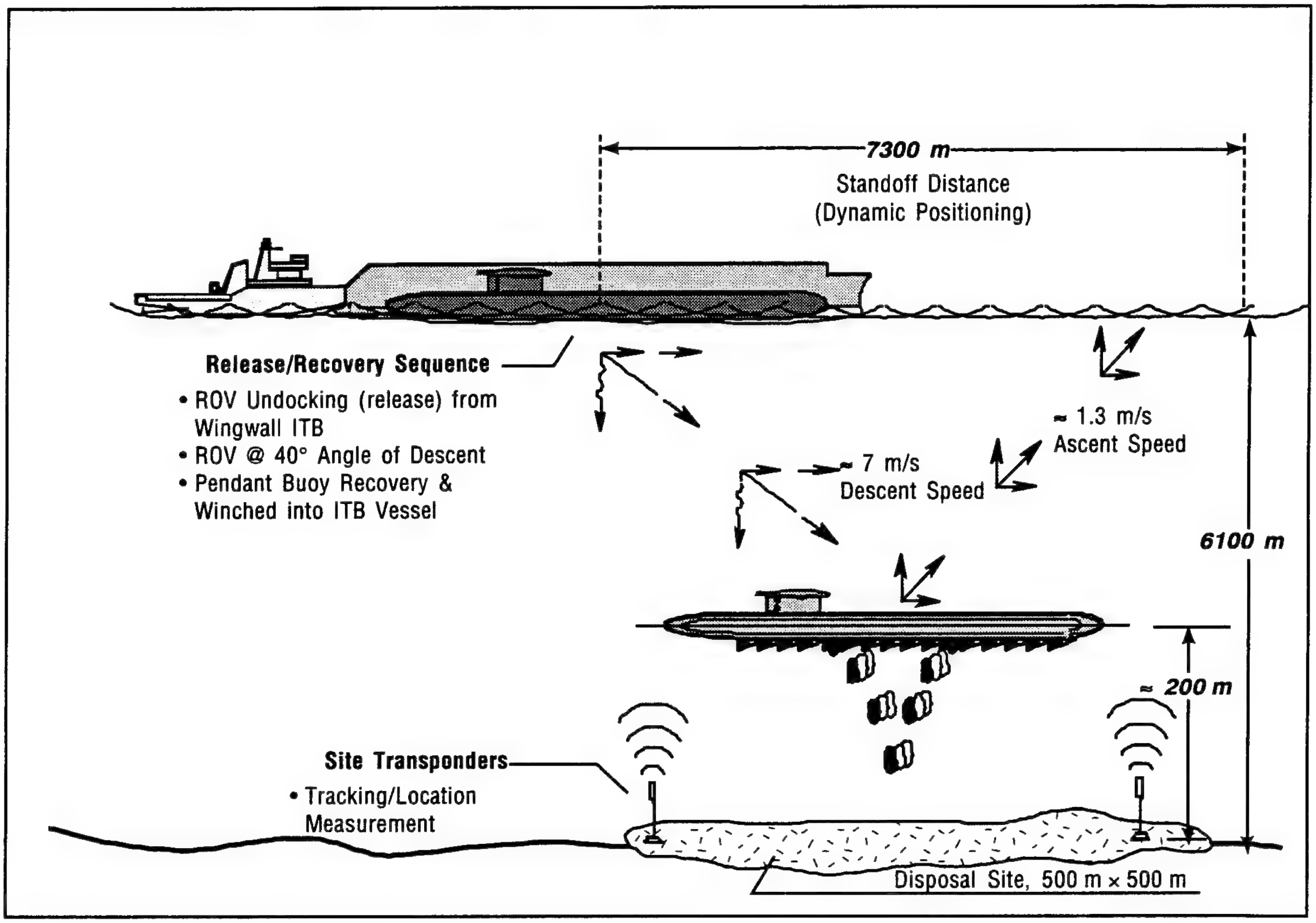

Figure 1.4.1-5. ROV glider concept employs a 25,000 DWT capacity autonomous vehicle to descend to abyssal depths, release its cargo, and return to the surface.

vertical (pitch) and lateral (yaw) planes. To achieve this positive static stability, the 130-m long ROV Glider has a horizontal stabilizer foil of 30-m span and 8-m chord at its aft end (see Fig 1.4.1-5). The desired glide path is achieved by adjusting the horizontal stabilizer angle-of-attack. The primary ROV Glider descent control will be onboard using preprogrammed flight plans with adaptive control; however, limited surface control can be accomplished using acoustic links.

Advantages of the ROV Glider concept are:

(a) Because this waste emplacement concept transports the full load of waste-containing bags to within 200 m of the seafloor, the potential impact on the ocean's euphotic zone because of bag rupture upon release is eliminated.

(b) Since bag release takes place within 200 m of the seafloor, the opportunity for horizontal fall path deviation (skating or sailing) of the bags is greatly reduced, thus ensuring a much tighter pattern of bags on the seafloor.

The ROV Glider concept does have some significant disadvantages:

(a) The concept function requires that 90% of the bagged waste cargo leave the glider to attain a neutral buoyancy condition. To achieve a reasonable ascent speed, near 100% release of the cargo must occur; thus, there is no margin of error to account for hang-up of release of the cargo cell trap doors or for hang-up of the bags in the cells.

(b) A potential for hang-up of waste-filled bags in the cargo cells due to differential pressure between the top and bottom of the cargo cells may exist. The entire glider hull serves as a foil during descent, with higher normal pressure on the underside of the glider as compared to the pressure on the topside. Analyses and model testing are required to verify that the differential pressure between top and bottom of each cargo cell will not be sufficient to impede waste-filled bag egress from the cargo cells.

(c) Emplacing the waste material within the 500-m × 500-m box may not be achievable by the ROV Glider concept. When the glider approaches this box from a location of about 7300-m distance horizontally at 11 m/s along its descent path, it takes only 15 min to reach an altitude 200 m above the seafloor where the waste-filled bags must be released. If the glider travels at 8.3 m/s across the seafloor, it must release its cargo from all 153 cells within 60 s if the bags are to stay within the 500-m box. Such precision of glider approach and cargo release will be difficult to achieve and maintain in practice.

(d) To achieve the positioning accuracy required in (c) above, reliable acoustic data transfer will be essential; however, flow noise generated by the glider moving through the water at 11 m/s and acoustic data transmission speed and integrity may preclude achieving the acoustic navigation needs of the ROV Glider concept.

(e) At-sea launch and recovery of the 130-m-long × 30-m-wide ROV Glider of 29,000 metric tons displacement at full load presents significant operational risk.

(3) **Direct Descent Disk**: The Direct Descent Disk concept is similar to the ROV Glider concept in that bagged waste is carried to near the seafloor by an autonomous transporter. The disk concept is quite different in that it is designed for no horizontal glide component and the payload per disk is one-fifth that of the ROV Glider. The disk shape was selected for this vertical descent transporter because, with proper fairing, that geometry is hydrodynamically

stable in free-fall. The disk path to the seafloor and the emplacement location of the waste cargo can therefore be predicted reliably (as shown by Atturio and Valent (1978) in work on free-fall-emplaced anchors). The Direct Descent Disk carries its waste cargo in polyester bag liners in 169 cargo cells in a "beehive" configuration. Each cell contains 19 m^3 (25 yd^3) of waste (Fig. 1.4.1-6), giving the disk a net negative displacement of 2085 metric tons. The disk is towed to the waste isolation site in a positively buoyant "garage" (much like the ROV Glider). When released from the garage, the disk free-falls at 6.7 m/s on a near-vertical path. At about 100 m above the seafloor, louvre-type drag brakes are engaged and the cargo cell trap doors open to release the bagged waste. With release of the waste cargo, the disk is 107 metric tons positively buoyant, and it returns to the ocean surface at 2.2 m/s. At the surface the disk is "captured" by its self-powered garage which then mates to the tug. For the Direct Descent Disk concept to be cost competitive, five units are transported on each trip. The "garage" sections are linked by an articulated latching system similar to types in present use (Hightower et al. 1995a, p 52).

Advantages of the Direct Descent Disk concept are:

(a) The Direct Descent Disk concept offers very accurate positioning of waste on the seafloor. This is achievable because of the hydrodynamically stable free-fall path of the disk and due to the short, 100-m fall distance of the waste-filled bags from the disk to the seafloor. The waste emplaced by one disk should be clustered within a 40-m diameter circle.

(b) The disk requires no active control during descent through the water column.

Disadvantages of the Direct Descent Disk concept are:

(a) The concept requires the open-ocean recovery of the five disks by their respective "garage" units, followed by recoupling of the "garage" units into the integrated tug/barge host vessel configuration. These decouple/recouple functions require realistic modeling and simulation to establish technical feasibility and competitive operating cost before proceeding with development of this concept.

(b) To develop the positive buoyancy necessary for the disk to return to the ocean surface, 98% of the waste cargo must release on command.

(c) The disks must be released at 500- to 1000-m spacing to ensure that ascending, empty disks do not collide with descending, loaded disks.

(d) The resurfaced disks are a hazard to navigation until all of the five disks are recovered.

(4) **Pipe Riser**: The Pipe Riser concept is part spar buoy and part single-point mooring buoy with product transfer capability (Fig. 1.4.1-7). Waste material flows by gravity down two 1.37-m (54-in.) OD high-density polyethylene (HDPE) pipes up to 7600 m (25,000 ft) length, exiting through a diffuser 100 m above the seafloor. This concept can emplace up to 4800 metric tons/hr. Dredged material and fly ash waste materials must be diluted from the transported condition to reduce the bulk density of the waste in order to limit the discharge flow velocity to less than 1.5 m/s (5.0 fps). Dilution and temperature adjustments are accomplished using seawater pumped from 760-m water depth in two additional 1.37-m OD HDPE pipes.

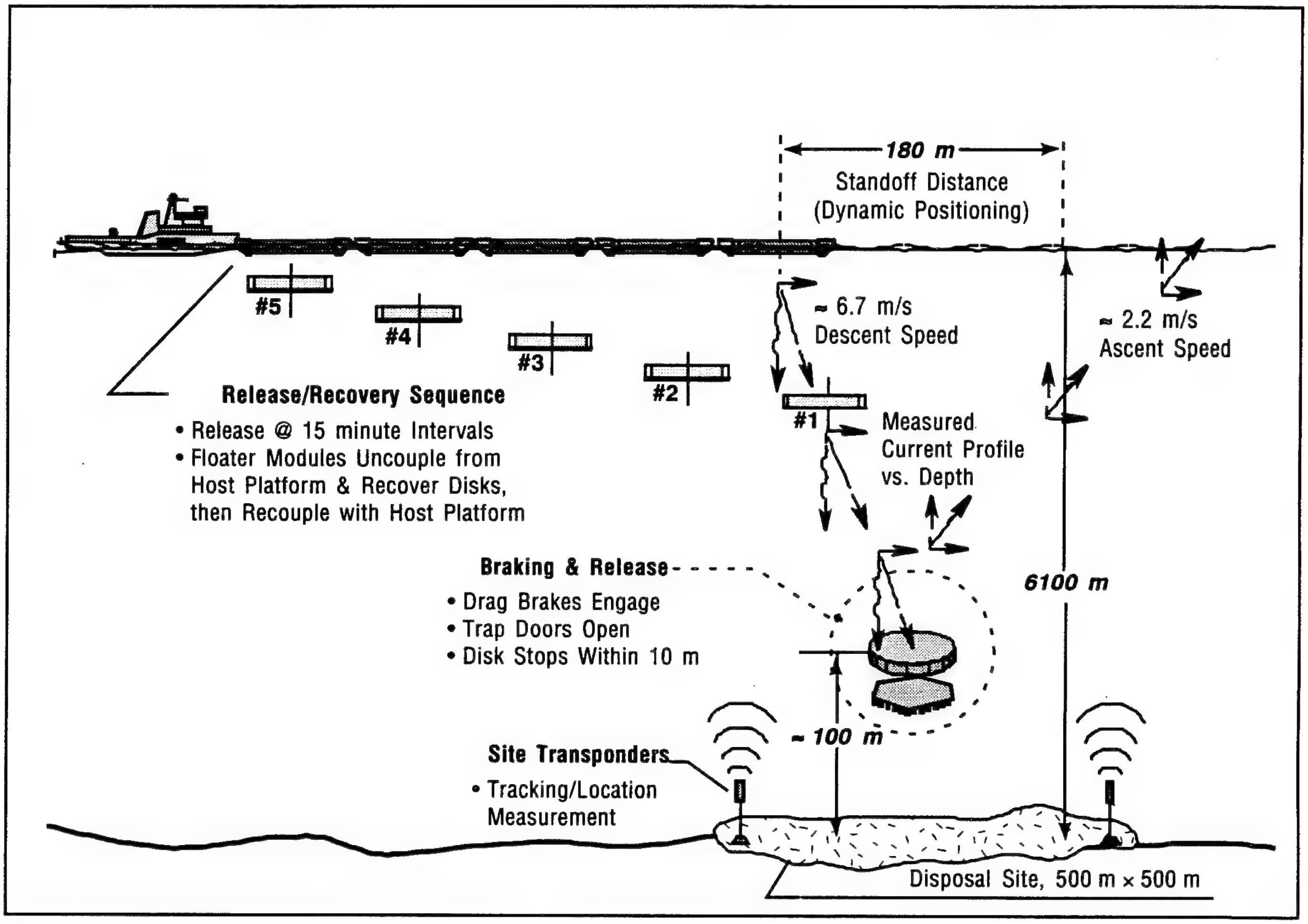

Figure 1.4.1-6. Direct descent disk concept uses 5 ea. 5000 DWT capacity modular elements to descend to abyssal depths, release its cargo, and return to the surface.

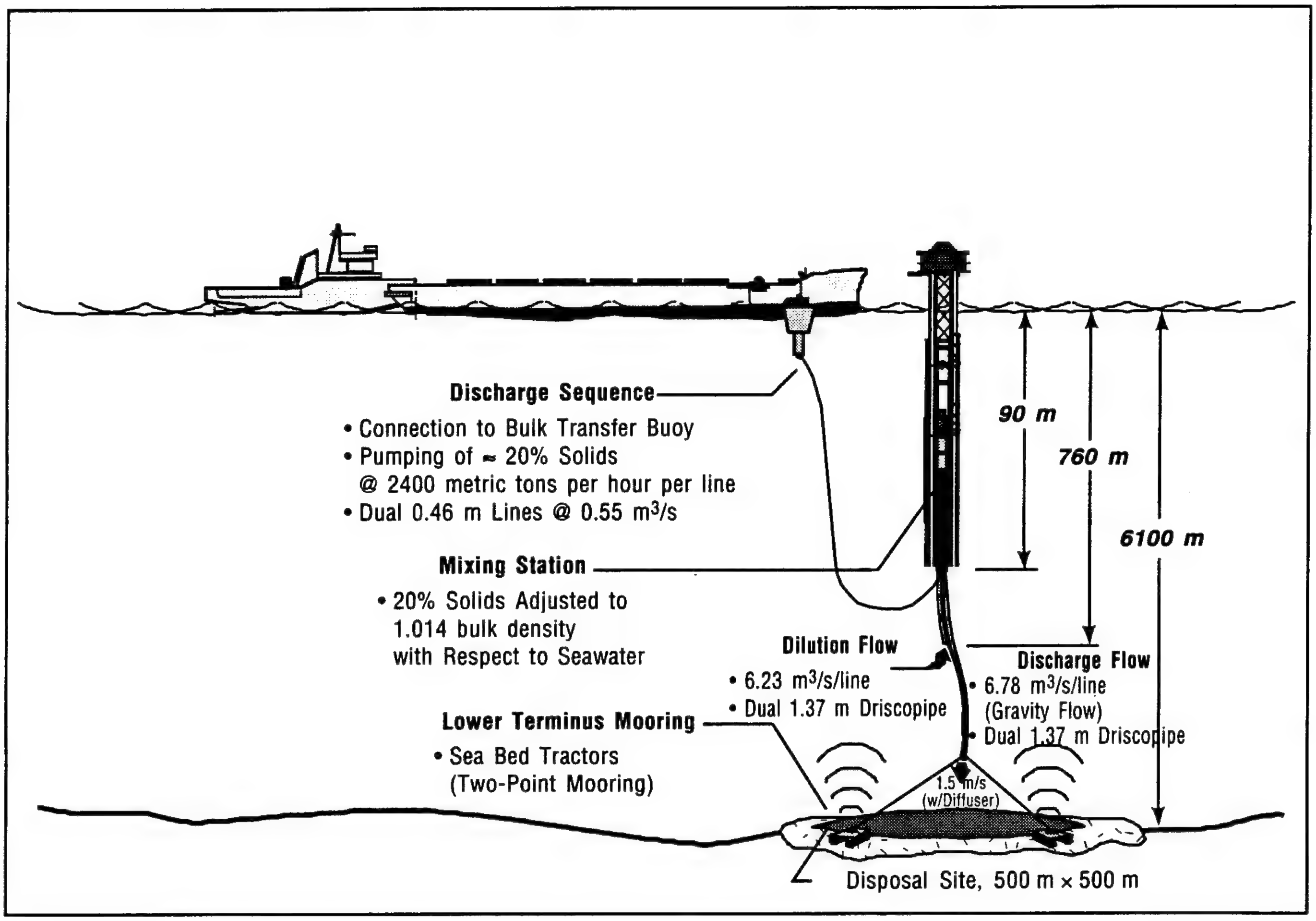

Figure 1.4.1-7. Pipe riser concept employs a dynamically positioned spar buoy assembly supporting pipe riser system to emplace 4800 metric tons/hour slurryized bulk waste.

The pipe riser stays on-station over the abyssal waste isolation site while transport ships of 25,000 DWT bulk cargo capacity haul the waste material from ports to the site. The wastes are pumped to the pipe riser via a transfer buoy and underwater flexible pipeline. Pipe riser stationkeeping is accomplished by an anchor system maintaining position of the seafloor end of the pipe riser and by a supplementary dynamic positioning system on the spar buoy at the sea surface (Hightower et al. 1995a).

Chief advantage of the Pipe Riser concept is the close positive control on the location of the discharge end of the riser and on the emplacement of wastes. A close second is elimination of the synthetic fabric bags integral to the three prior presented concepts. The synthetic fabric bags account for 20% of the operating cost of the previous concepts, thus elimination of the bags is a significant cost savings. Another possible advantage of the Pipe Riser concept is the capability to efficiently and effectively spread a cap of clean sand material over the wastes. This cap should practically eliminate potential for contaminant transport by resuspension due to scour and by burrowing benthic organisms.

While the advantages of the Pipe Riser concept are significant, so also are its disadvantages:

(a) Because of the complexity of the Pipe Riser concept and because one riser would serve ports on an entire coast, e.g., one riser serving the entire U.S. east coast, the system reliability must be very high, requiring a high degree of redundancy in all critical subsystems.

(b) The system must be capable of surviving all potential weather conditions on-station because the time needed to move the pipe riser exceeds the expected warning time, and the cost of moving the system is prohibitive.

(c) Components of the Pipe Riser concept, such as the length of the continuous HDPE pipe and its installation, the seabed tractors/anchors, and the waste handling pumping systems, are about 20 times larger in size than present state-of-the-art. Therefore, the concept involves significant risk.

(d) Maintenance of the Pipe Riser concept is expected to require intervention by Remotely Operated Vehicles (ROVs) at great depths. Such ROV operations are complex and very difficult, and entertain potential for significant cost escalation.

(5) **Tethered Container**: The Tethered Container concept employs a 191 m^3 bottom-dump bucket carrying 250 metric tons of waste to the abyssal seafloor isolation site (Fig. 1.4.1-8) with no loss of material to the intervening water column and with good positioning control. The bucket capacity is limited to about 250 metric tons because of limits on expected synthetic load line manufacturing capability, the dynamic loading of the system due to ship/handling platform motion in the open sea, and the expected limits on winch and line storage spool capacities. Round-trip time for the tethered container is projected at 1.05 hr, yielding a waste emplacement rate of 240 metric tons per hr. This waste emplacement rate is one-twentieth that of the 4800 metric tons/hr rate minimum projected for economic viability of the abyssal ocean-isolation option. Further, the service life of the synthetic line tether is expected to be unacceptably short due to premature fatigue failure. This is because the natural frequency of the tether is about same range as those frequencies input by ship motion and by strumming due to current vortex shedding.

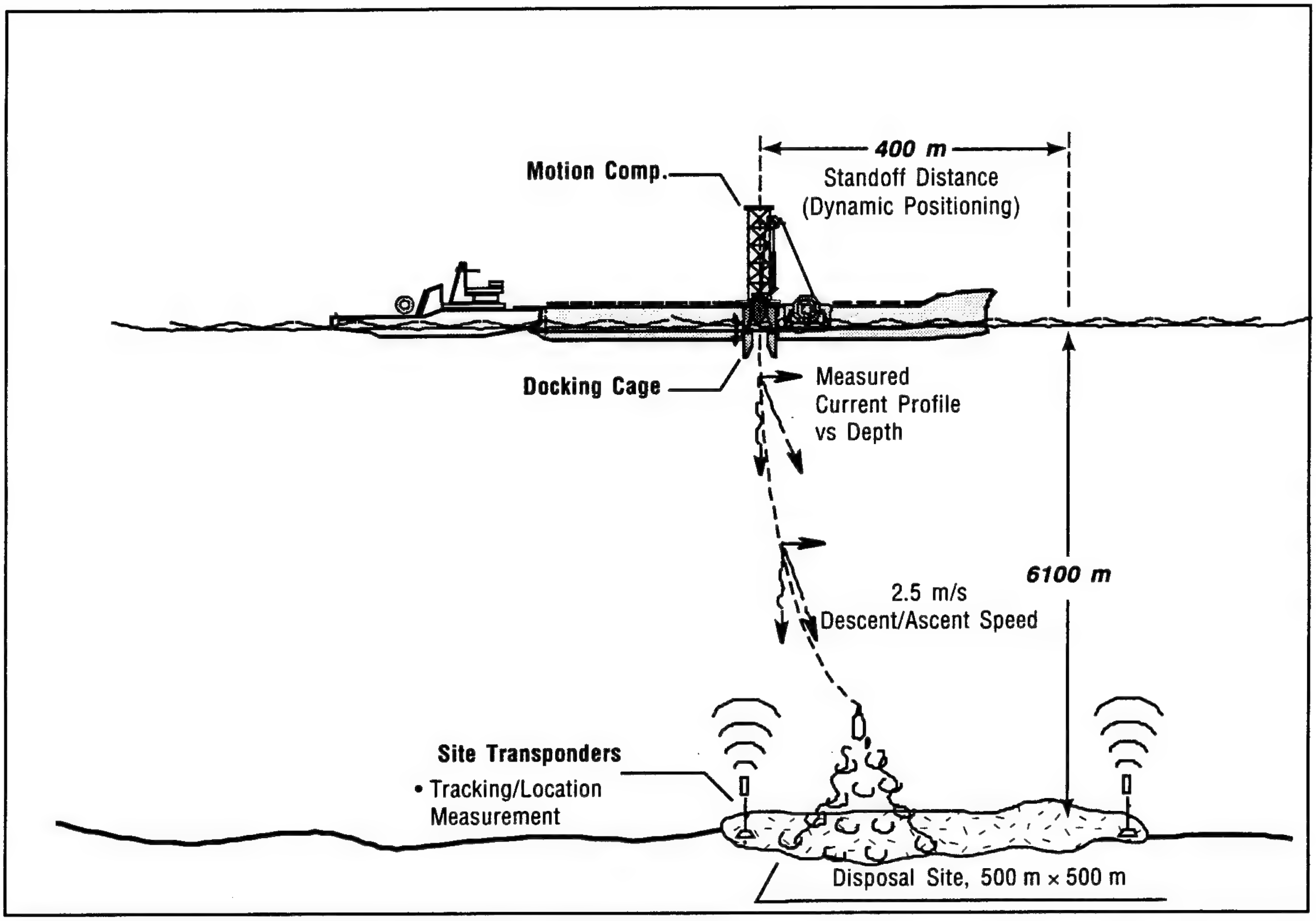

Figure 1.4.1-8. Tethered container uses a 190 m^3 capacity container for deposit of 240 metric tons/hour bulk waste into APWI project isolation site.

In summary, the Tethered Container concept is not a viable option for abyssal seafloor waste isolation.

1.4.1.4 Reliability Analyses

The Surface Emplacement, ROV Glider, Direct Descent Disk, and Pipe Riser concepts were subjected to two independent forms of reliability analyses: (1) the Fault Tree Analysis (FTA) and (2) the Failure Modes, Effects, and Criticality Analysis (FMECA).

The FTA is a top-down, graphical design analysis technique used exclusively in Reliability, Safety, and Maintainability engineering. Fault Trees generated for all mission scenarios and segment elements identified no major risks that cannot be mitigated either through redundancy or operating procedures. In this analytical technique, the risks were not quantified in either severity or probability of occurrence, but the FTA made clear that the Pipe Riser concept entails more reliability-related risks than any other concept (Hightower et al. 1995a, pp 113–121).

The FMECA is a bottom-up analysis of failures caused by hardware, software, and human error. This analysis was performed in accordance with the intent of MIL-STD-1629A, "Procedures for Performing a Failure Mode, Effect, and Criticality Matrix." All possible failure modes of concept functions or components and their effects on the mission and environment were analyzed, and each failure mode was assigned a qualitative probability value. These failure mode probabilities were then combined with a quantification of the severity of effect of that failure and integrated for each concept to yield calculated weighted risk indices. This approach allows a qualitative comparison of relative risk between the concepts. The risk-ranking indicates that the Surface Emplacement concept offers the least operational risk, and the Pipe Riser concept is clearly the concept with the highest risk (Table 1.4.1-4). The ROV Glider and Direct Descent Disk concepts rank essentially equal in FMECA (Hightower et al. 1995a).

1.4.1.5 Construction and Operating Cost Estimates

Capital costs and annual operating costs for each of the four technically viable concepts were developed to determine economic viability and attractiveness of each concept. This cost comparison does not include technology development costs. These are addressed briefly in Section 6.2, **Science and Technology Development Costs**. Further, the cost comparisons herein do not include the cost of transporting wastes from their source (e.g., municipal sewage treatment plant) to the ASWI port-loading facilities. At this stage of analysis, these costs are projected to be the same for all concepts; therefore, their inclusion would not change results of this comparison of concept costs. Total costs for each of the concepts is covered in a project report devoted to that subject (Jin et al. 1995).

Capital and annual operating costs for each concept were calculated separately for: (1) sewage sludge and fly ash, and (2) dredged material. This separation was necessary because of significant differences in the waste material source location and rate of supply. The results, presented in Table 1.4.1-5, indicate relatively similar costs because operating

Table 1.4.1-4. Calculated weighted risk indices for the four candidate waste emplacement concepts (lower score indicates lower risk). These scores allow a comparsion of relative risk between the concepts and are not intended to represent absolute risk values.

Surface Emplacement	34
ROV Glider	101
Direct Descent Disk	95
Pipe Riser	147

Table 1.4.1-5. Summary of projected emplacement costs (capital and operational costs, port to seafloor, only) for wastes via each of the four candidate emplacement concepts ($ per unit).

Concept	Cost per metric ton of Sewage Sludge and Fly Ash	Cost per unit volume of Dredged Material
Surface Emplacement	15	$16/m^3$ $(12/yd^3)$
ROV Glider	20	$21/m^3$ $(16/yd^3)$
Direct Descent Disk	24	$26/m^3$ $(20/yd^3)$
Pipe Riser	18	$20/m^3$ $(15/yd^3)$

costs for each system are very similar and because the volume of waste is very large, resulting in the operating costs overshadowing the capital costs. The Surface Emplacement concept is indicated to be the most cost efficient, even though the disposable fabric bags are a large cost contributor (bags account for 20% of the emplacement cost) (Hightower et al. 1994a). The projected low cost of the Pipe Riser concept is due, in part, to the elimination of the high-cost, disposable bags. This cost comparison does not include the costs of technology development which are expected to be very high for the Pipe Riser concept.

1.4.1.6 Summary of Significant Points for Environmental Assessment

The Technical Assessment Task and the engineering concepts evolved from that task have identified a number concerns relative to the process for emplacing wastes on the abyssal seafloor. These concerns are important for assessing the short- and long-term impact of such emplacement on the abyssal environment. The more significant of these items are:

(1) To facilitate monitoring of the potential waste isolation sites, the project team chose to limit isolation site size to box-shaped areas 500 m on a side. The Technical Assessment Task has shown that limiting the size of each isolation site to such dimensions is not technically feasible. For the Surface Emplacement concept, model and field performance data for the waste-filled bags are not available for calibration of a free-fall path deviation model. However, it does appear likely that probable differences in waste density distribution within the bag cargo could result in a deviation from expected fall path over 6100 m of more than 250 m (thus some of the released bags could come to rest outside the designated box). The ROV Glider concept would have to have a perfect approach to the isolation site with every cargo because release must begin exactly at the beginning of the box in order to have all cargo released before the glider, traversing the site at 11 m/s, exits the far side of the box. The Direct Descent Disk concept envisions spacing the five disks for each trip at 500- to 1000-m intervals to limit potential for descending disks colliding with ascending disks. The Pipe Riser concept is the only technically-feasible concept that could achieve the goal of maintaining emplacement within a 500-m × 500-m box. That concept is probably too risky and costly to become a reality. A more technically feasible waste isolation area would be a box 3000 m on a side or a circle of 3000-m diameter.

(2) Waste-filled fabric bags reaching virgin abyssal seafloor will most likely not rupture or tear upon landing (COE experience to date indicates that far greater potential for rupture or tearing exists as the bag exits the cargo cell). However, a large factor in reducing stresses in the bag upon landing is the trapped-water effect on the flat seafloor surface. For subsequent waste bags approaching a seafloor strewn with prior emplaced waste-filled bags, the water cushioning effect on the now highly irregular landing surface could be much reduced, leading to rupture of landing and/or prior-placed bags. Thus, even for those concepts using fabric bags to isolate the waste during free-fall to the seafloor, the resulting waste deposit will likely include a significant volume of uncontained waste material. (Only a large, full-scale experiment would emplace a sufficient amount of material and bags to provide for clearly understanding and predicting results.)

(3) The resulting waste deposit on the seafloor is expected to have maximum slopes no greater than about 4°, with an "apron" of the finest material that has flowed from the main

pile with slopes of less than 1°. Expected waste material thicknesses at the center of the isolation site resulting from one year's deposition, from one major embarkation port, range from 10 to 25 m.

(4) Sewage sludge, with its bulk specific gravity of 1.04, to be managed in the deep-ocean isolation option, must be "weighted" with another, more dense material. For this analysis the weighting has been obtained by assuming fly ash (but the weighting material could also be a fine sand or silty sand) is partially mixed with sewage sludge during the waste transfer process at the embarkation port to yield a bulk specific gravity of 1.25. This partial mixing could be accomplished in the screw conveyor system, but the process would not yield a homogenous combination. For purposes of this analysis, the sewage sludge component would be effectively contained in the fabric bags during descent, but if the bag is breached on the seafloor, the sewage sludge component could easily be transported along the seafloor by very slow currents found at the abyssal waste isolation sites. The potential and significance of this transport mechanism merits detailed review in any subsequent work. This concern regarding transport applies to the sewage sludge due to its low bulk density, but does not apply to dredged material and fly ash.

1.4.2 Bag Compositional Breakdown *by Alan W. Webb*

An alternative method to emplacing waste material in a loose condition on the abyssal seafloor is to contain it in large polymeric bags which are then dropped to the seafloor (see Section 1.4.1, **Engineering Concepts**). By selection of appropriate woven outer bags for strength, along with inner nonwoven liners for containment of fines, material can readily be emplaced on the abyssal seafloor with minimal interaction with the intervening water column. This technique has already been used both in Europe (especially the Netherlands) as well as in the U.S. for both surface (beach erosion control, dikes, expansion of islands) and subsurface (protection of shipping channels from silting) applications as detailed in the ASWI Engineering Report (Hightower et al. 1994b).

Basically there are two types of polymers in use for formation of such fabrics, often termed geotextiles, viz., polypropylene (PP) and polyester (PS). Due to differences in their chemical makeup and their method of formation, they each have unique characteristics to consider in any application. Both PP and PS geotextiles are produced by Nicolon Mirafi, while Amoco produces only PP fabric.

PS is inherently stable to exposure to ultraviolet light (UV), while PP is susceptible to UV-induced degradation. For this reason, PP typically has a filler of carbon black, along with additives such as hindered amine light stabilizers. This renders PP black, while PS is off-white. The PP is normally exposed to light for a matter of only 1–2 weeks in application, so the degradation is minimal. Emplacement of this fabric in abyssal depths would shield it from any further exposure to light. The very-long-term effects of this initial exposure are not known, and need study.

PP undergoes negligible hydrolysis in a high-humidity or aqueous environment, whereas PS undergoes a slow strength loss. These effects appear, by extrapolation, to be minimal, as will be described.

The density of PP is 0.91 g/cm^3; PS has a higher density of 1.022–1.38 g/cm^3. Because the density of PP is less than that of seawater, the bag fabric itself would float to the ocean surface if freed from the contained waste as through deterioration of the bag material or its stitching or through tearing of the bag. Because of this remote possibility of generating floatable polymeric wastes, it is unlikely that PP would be used for the waste container fabric. (While use of polymeric fabric to contain wastes for transport and emplacement on the abyssal seafloor is not outlawed by U.S. [40 CFR 227.5] and international law [IMO 1991, 1992, Annex V], the use of potentially floatable fabrics would violate the spirit and intent of these agreements and, with availability of PS fabric, use of PP materials would be not only unnecessary, but also inappropriate.)

The kinetic theory of polymer strength provides a basis for estimating the effects of the extremes of conditions on the long-term utility of polymers when only data limited to near-ambient conditions are available. In this theory, the long-term strength is considered to reflect the average rate of degradation processes at all levels, i.e., molecular, supermolecular, and macroscopic, which is accomplished through the Zhurkov equation:

$$\tau = \tau_0 \exp\left[\frac{U_0 - \gamma\sigma}{kT}\right],$$

where τ is the time to decomposition of the molecule at temperature T and mechanical stress σ; τ_0 is the oscillation period of chemically bonded atoms, U_0 is the activation energy of the process (the energy required to break the chemical bond), k is Boltzmann's constant, and γ is the coefficient of transformation of mechanical stress to energy. This factor τ is also described as the long-term strength, since it has been shown experimentally in a vast number of solids of varied chemical nature that this equation describes the macroscopic degradation where many bonds are strained and subjected to nonuniform stress resulting in bond ruptures being distributed in both time and space. This equation was also found to describe the kinetics of the accumulation of submicrocracks (Emanuel and Buchachenko 1987).

The effect of pressure on polystyrene under hydrostatic compression has been studied (Emanuel and Buchachenko 1987, p 261). It was found that increasing the pressure from ambient to 6000 bar increased the long-term strength by 10 orders of magnitude. The source of this increase lies mainly in the linear increase in the activation energy, U_0, from 31 to 72 kcal/mol.

The depths of the abyssal plains give rise to pressures of the order of 300 bar, about 5% that used in the above study. However, considering the tremendous effect reported, it is expected that even this more modest increase in pressure will markedly increase the strength of polymers placed in this environment. Pressure stability studies are needed for the two materials peculiar to this application, namely PP and PS, to verify the extension of these results, and to establish the extent of the effect.

The effect of the temperature of the abyssal ocean, being ~4°C on the average, is also expected to have an effect. Nicolon (1994) reported on residual strength tests which were run for 120 days at 95°C, and then modeled for comparison with data taken at 80°C. The comparison was good. Extrapolated results from the model were then developed at 30°C and 20°C. A 90% residual strength was extrapolated for 300 years at the lower temperature. Using best-fit values, a residual strength >95% is expected for material kept at 0°C for a thousand years. The temperature extrapolations are admittedly very long. However, both the thermal and the pressure results combine to strongly suggest that bag material would persist for very-long-term periods under the environmental conditions in abyssal depths of the ocean. Extended studies of a very long term (in the laboratory timeframe) are needed to verify these extrapolations, or at least to verify the model over a longer interval, thus increasing confidence in its application.

Unanswered at this point is the effect of the strongly reducing environment experienced by the fabric at the abyssal sediment surface under the bagged-emplaced materials. However, even if a deterioration process were to take place there, it is expected that the overburden would continue to retain the products.

1.5 Past Studies

1.5.1 Deep-Ocean Mining *by William B. Sawyer*

Seafloor deposits enriched in certain metals (ferromanganese nodule deposits) were first sampled by the British research vessel HMS *Challenger* in the pioneering expedition of the World's oceans (1873–1876). Some of the world's ferromanganese nodule provinces are identified in Section 3.2, **Mapping**. Previous environmental impact studies associated with deep-ocean mining of manganese nodules, metalliferous sediments, and polymetallic oxides and sulfides have focused on determining water column and seafloor ecosystem impacts resulting from the removal of these mineral resources from the bottom, subsequent disposal of the tailings from surface-ship processing, and sediment plume development and dispersal within the water column.

Gerard (1976) compares the environmental effects of naturally occurring ocean and seafloor phenomena to those effects that would occur in the deep-sea following manganese nodule mining activities. Gerard discusses the effects of naturally occurring sedimentological events, which introduce large amounts of sediment into the water column and onto the seafloor, such as turbidity currents, large sediment discharges from major rivers (Amazon and Congo Rivers), and submarine slumps resulting from seafloor slope instabilities. He then compares those events with those analogous effects associated with removing seafloor mineral resources and the resuspension-deposition of seafloor sediments associated with these mining operations. Gerard concludes that "...order of magnitude..." estimates of expected environmental effects could be drawn from this analogy.

Scott (1992) states that the removal of polymetallic sulfides differs from the removal of manganese nodules in the amount of seafloor area which is impacted. Manganese nodule mining disturbs large areas affected by nodule removal operations, whereas polymetallic

sulfide mining is limited to much smaller areas and hence would have less environmental impact. Additionally, there would be far less waste rock from the mining of the sulfide deposits as compared to that of manganese nodule mining. He states, however, that the conventional flotation method for concentrating the acidic sulfide deposits and removing the oxide films, requiring the addition of "...noxious chemicals...," would be an environmental concern in disposing of the tailings. Scott (1992) recommends test mining a small, biologically inactive area and subsequent close monitoring of the environmental impact from the test.

Exon et al. (1992) describes a coordinated plan for assessing the environmental effects of mining manganese nodules from the seabed. In this plan he recommends investigations dealing with understanding the deep-sea environment via long-term measurements of the bottom current and current regime. Other studies investigating the chemical composition of the bottom water, the nature of the bottom sediments, and the benthic and planktonic communities are required before mining begins. Subsequent to small-scale mining experiments, additional studies of the disturbance/effects should focus on the plume generated from the mining activity, the changes in the bottom water chemistry and sediments, and the disturbance and recovery of the biological communities. The scale of the mining experiments should provide sufficient environmental information for extrapolation to full-scale mining, and large-scale experiments are recommended. Bluhm (1993) concludes that monitoring of pilot mining experiments and pilot operations should be proposed and conducted by commercial mining companies before production mining begins to determine effects on the abyssal environment.

Yamazaki (1990) suggests that mining manganese nodules will disturb the near-surface ocean waters from extraction of cold bottom water and that the discharge of this water by the surface mining vessel may have a major environmental impact due to the introduction of nutrient-rich bottom water, which contains suspended sediments and finer fragments of nodules. The resuspended sediments disturbed by the nodule collector system will create a benthic plume and subsequently be redeposited and blanket the seafloor and impact the benthic communities. Yamazaki (1990) states that field monitoring of the environment and benthic plume are closely associated with pilot test mining activities.

Thiel (1991) presents a historical perspective of deep-sea mining and associated environmental effects from experiences gained in two projects: Metalliferous Sediment Atlantis II Deep (MESEDA) and **Dis**turbance and Re**col**onization of a Manganese Nodule Area in the south Pacific (DISCOL)). Studies associated with the MESEDA project in assessing environmental impact dealt with varied subjects such as seafloor morphology, sedimentology and geochemistry; general circulation patterns, temperature, salinity and water chemistry, and composition of the biota. Additional environmental studies focused on determining heavy metal distributions in seawater, sediment, and organisms; chemical composition and toxic nature of the tailings; and environmental effects associated with the disposal of the tailings. Ecologists in this mining study proposed deep discharge of tailings via a pipeline (below 1000 m) so as not to impact the vertically migrating flora and fauna which were observed to migrate vertically to depths of up to 750 m. The tailings were determined to be toxic and toxicity tests performed on zooplankton, phytoplankton, and hydroids showed that leaching of substances in the particulate phase of these tailings

resulted in decreased growth rates in the these test organisms. In particular, Karbe and Nasr (1981) state that plume models and plume observations are not coherent and larger test mining studies are required to address this issue. Karbe and Nasr further state, in a draft environmental statement, that the fate of the "...dissolved mining phase..." is undetermined; metals concentration is high and is toxic to test organisms, and further research of these toxic effects is required; the effect of the tailings on the plankton via bioaccumulation of toxic materials and potential for food chain effects are "not well understood;" and effects on the benthos are not predictable from plume modeling of the particulate and dissolved phases.

The Deep Ocean Mining Environmental Study (DOMES) was also reviewed by Thiel (1991). This study was conducted by the National Oceanic and Atmospheric Administration. The results of this study, as well as results from the MESEDA project, showed that from all the gathered environmental information, extrapolation to expected effects which would occur from full-scale commercial mining activities is not possible, and larger-scale experiments are required.

The DISCOL study was conducted utilizing a plow-harrow device to disturb the seafloor within the experimental area and mimic the effects of the nodule collector system used in actual mining operations (Thiel 1991). This study concluded that the removal of nodules from the seafloor would result in sedentary fauna having little chance for recolonization and that the nodule crevice fauna will lose their habitat; however, stalked species recovered from the disturbance caused by the sediment plume. It was concluded in this study, as in others, that large-scale experiments into the environmental impacts of mining should be conducted to allow for extrapolation to full-scale commercial mining. Bluhm (1993) observes that mining activities that strip the seafloor of manganese nodules will result in hard-bottom living fauna being displaced by soft-bottom communities and that diversity will decrease. Sessile organisms, such as sponges, crinoids, and gorgonians, did not recolonize the DISCOL experimental area for 3 years after the initial disturbance created by the plow-harrow (Bluhm 1993).

The potential for commercial mining of these metalliferous seafloor deposits has waxed and waned in recent years due to fluctuating world market prices for metals and due to certain language within the United Nations Law of the Sea (UNLOS), which was unfavorable to the commercial deep-ocean mining industry (Thiel 1991). Thiel stated that technology development within this industry has decreased to very low levels, with the exception of a few ongoing government-funded programs. [Note that recent changes in UNLOS resulted in the removal of specific language dealing with protection of land-based producers via ocean-mining production limitations (Nelson 1994)].

1.5.2 106-Mile Ocean Disposal Site *by Michael D. Richardson*

The 106-mile ocean disposal site is probably the most studied deep-ocean disposal activity in history. Sewage sludge and a variety of industrial wastes had been deposited in the New York Bight for several hundred years. Most disposal occurred at the 12-mile site in the apex of New York Bight (see Section 1.5.5, **MESA/New York Bight Studies**). With the legally mandated closure of shallow-water disposal sites, EPA established the 106-mile Deep Water Municipal Sludge Dump Site (106-Mile Site) off the New Jersey coast. This

256 km^2 site was located seaward of the continental slope/shelf break (2400- to 2700-m water depths) within a rectangular area bounded by 38°49'N to 39°00'N and 72°00'W to 72°05'W. Disposal of sewage sludge from nine New York and New Jersey sewage waste authorities began in March 1986. The Ocean-Dumping Ban Act (ODBA) of 1988 subsequently prohibited ocean dumping of sewage sludge and industrial wastes starting in 1991. At the cessation of disposal of sewage sludge, in June 1992, approximately 42 million tons (wet weight) of sewage had been barged to the 106-mile site and dumped into the surface mixed layer. In response to the ODBA, sewage sludge, at least from New York, is currently being used for composting, land application, land reclamation or placed in landfills (Swanson 1994).

The EPA, National Oceanic and Atmospheric Administration (NOAA), and the United States Coast Guard (USCG) were all charged with the development of a strategy for monitoring, research, and surveillance of activities at the 106-Mile Site (EPA 1989). From the start, the plan called for dispersal rather than isolation of waste material. Primary concerns of the EPA, NOAA, and USCG study included the following: (1) what is the physical and chemical fate of sewage sludge dumped at the 106-Mile Site, (2) what is the effect of the sludge dumping on living marine resources, and (3) what is the effect of sludge dumping on human health? Initial conclusions, based on early studies by the EPA and NOAA (1984–1988), were that impacts of disposal of sewage sludge at 106-Mile Site would have little or no adverse impact on living resources or human health. Oceanographic circulation studies and models suggested rapid dispersal of dumped materials with no sewage sludge moving into coastal waters or onto the beach. No appreciable adverse effects on bottom fauna were predicted (EPA 1989).

Under the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972 and subsequent amendments (ODBA 1988), NOAA had the responsibility to conduct research at the 106-Mile Site, whereas EPA and USCG were responsible for surveillance (site designation, permits, and monitoring) of disposal operations. Monitoring, primarily an EPA responsibility, was divided into four Tiers: Tier I, sludge characteristics and disposal operations; Tier II, near-field fate and short-term effects; Tier III, far-field fate; Tier IV, long-term effects (Battelle 1990).

In a summary of EPA studies from 1986 through 1990, Redford et al. (1992) reviewed findings of initial monitoring studies as well as initial studies on the fate and effects of sewage sludge disposed at 106-Mile Site. The plume and associated chemical tracers, generated by disposal of sewage material, were primarily advected at random directions in the short-term, with long-term transport towards the southwest. Dilution was rapid with little short-term biological effects on plankton. Most transport was advective, restricted to surface water, with no more than 10–20% of the material settling to below the pycnocline within 350 km of the disposal site. These results are in agreement with models developed by the USCG (Fry and Butman 1991). Although near-field monitoring of concentrations of sludge constituents frequently did not meet 4-hr EPA regulatory requirements, little short-term adverse biological effects were detected. Other studies (Sayles et al. 1993; Van Dover et al. 1992; Grassle 1990) suggest sewage sludge has settled on the bottom at the 106-Mile Site and has had a measurable effect on both benthic boundary layer biogeochemical cycles and on the composition of bottom fauna. Chang (1993) found a reduction in finfish stock

correlated with dumping but was unable to establish cause and effect relationships. Battelle Ocean Sciences Reports to EPA (1992, 1993) document sewage sludge deposition on the seafloor with the use of sediment traps. Most of the sewage sludge was associated with larger size particles or flocs and was concentrated at and southwest of 106-Mile Site. There was no evidence for transport or deposition of sewage material on the continental shelf. The combined results of various 106-Mile Site experimental studies and circulation models have resulted in the following estimated distribution of sewage sludge: 68% suspended in upper slopewater; 28% deposited on slope bottoms; 2% suspended in lower slopewaters; 1% suspended in shelfwaters; 0.8% deposited on shelf sediments (Battelle 1993).

Much can still be learned from the ongoing 106-Mile Site studies. Results of studies of transport and far-field fate of sludge material, as well as long-term effects of sewage sludge such as bioaccumulation, shellfish, and finfish disease, and effects on pelagic and benthic communities, were presented at a symposium on the 106-Mile dump site held at State University of New York, October 25–28, 1993 (SUNY 1993). In general, the impact of disposal of sewage sludge at the 106-Mile Site appears less deleterious to man and marine resources than at the shallow 12-Mile Site. The fact that nearly 25% of the sludge material was deposited at slope depths at and southwest of 106-Mile Site is of great concern, although preliminary indications show a very rapid recovery of the natural biogeochemical conditions and of the natural fauna after cessation of disposal operations. Lessons learned from study of the 106-Mile Site disposal operations are best applied to the far-field effects of an isolation scenario, which is the subject of this report. When all the results from the 106-Mile study have been published, this topic should be revisited.

1.5.3 Studies of Radioactive Waste Disposal *by Gilbert T. Rowe*

The study of radioactive wastes in the ocean has provided considerable information related to the concept of isolating wastes, as defined in this study, on the abyssal seafloor. The general health and ecological issues associated with radioactivity in the environment, both land and aquatic, have been dealt with in numerous texts, government reports, and scientific journal articles. Two succinct accounts which cover the entirety of the field have been published by the League of Women Voters (1985) and Pentreath (1980). Nuclear power generation, weapons production, and medical wastes produce two broad categories of radioactive waste: high level, which is produced in relatively small volumes, and low level, which is rather dilute but is produced in large volumes. The latter has been routinely released in a controlled fashion into the environment. In the ocean this has been in effluents near power-generating stations and at fuel processing plants, such as Sellafield on the west coast of Great Britain. Low-level wastes have also been stored in solid form in a variety of semipermanent locations, mostly on land, but on occasion in the deep ocean. Both the controlled release of dilute liquid wastes and low-level disposal of canisters of waste, mostly in the form of 55-gallon drums filled with cement, have been studied extensively. The Office of Radiation Programs at the EPA has produced a series of documents describing the conditions at waste sites off the U.S. east coast at 2.8- to 3.7-km depth and near the Farallon Islands off San Francisco, CA, at depths of over 2 km. The DSRV ALVIN has been used, as well as remote vehicles, to sample sediments and fauna on and near waste canisters at these sites. Studies of ^{137}Cs and ^{134}Cs document releases from canisters that suggest

the sediments act as a barrier, and that bioturbation is the dominant agent redistributing these radionuclides (Dayal et al. 1979). One such canister was recovered by engineers of the Brookhaven National Laboratory, using ALVIN, for observation on its resistance to corrosion and release of radionuclides in the laboratory. A report from hearings by the Committee on Merchant Marine and Fisheries, of the U.S. House of Representatives, dealing with Ocean Dumping and Pollution, covered the issue of low-level waste disposal in detail (Congressional Record, H.R. 4715, H.R. 5282, H.R. 5851, Serial No. 95-42, 1977 and 1978; and Serial No. 96-53, 1980). The dumping activities and ensuing studies by the EPA were also reviewed by the General Accounting Office (GAO 1981). In summary: the small amounts of low-level waste dumped have done no particular damage. They have allowed marine scientists to demonstrate that relocating such areas and sampling them is possible with available technology. However, as GAO points out, a complete and accurate accounting of how much material was dumped into U.S. waters between 1946 and 1970 is not possible.

In Europe the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has sponsored investigations of a low-level waste dump site at a water depth of ca. 4 km situated just outside of the Bay of Biscay, north of Portugal. A thorough review of the continued suitability of that site for such dumping was conducted (OECD 1985). The OECD volume includes the legal framework within which dumping was conducted; a description of the waste forms and quantities put there; a description of the area, including the biota, currents, sediment types, etc.; a radiological assessment of the site which included a variety of models addressing the dose delivery of radionuclides to critical groups arising from a range of dumping practices and sensitivity analyses; and a discussion of how the practice of dumping at that time conformed to specific guidelines required by the London Dumping Convention (LDC) and the International Atomic Energy Agency (IAEA).

A hierarchy of models were used by the NEA in their assessments: physical advection and dispersion across a wide range of time and space scales, waste form release rates, scavenging by particles, and food chain transfers. These would each have application in the present studies of waste storage on the abyssal seafloor. Likewise, a number of independent efforts have attempted various models concerned with the question of radionuclide transfers in the deep ocean. As Great Britain was a major user of the deep low-level site, as well as introducing considerably greater quantities at Sellafield, the British have had an interest in its fate (Webb and Morley 1973; Shepherd 1976; 1980; Pentreath 1980). United Nations-sponsored agencies have also contributed independently to assessment of potential physical transfers in the deep ocean (GESAMP 1983). This UN work also led to independent assessments of the relationship between physical transfers and isolated ecological situations in which competing biological concentration and transfer could be important from a radiological safety perspective (Rowe et al. 1986).

While high-level radioactive wastes have not been purposefully disposed of in the deep ocean by western nations (to our knowledge), the concept of storing high-level, e.g., heat-producing waste, within deep-sea sediments has been actively studied, both in the U.S. and in the OECD. Nuclear submarine accidents have provided some information on the fate of radionuclides (Sheldon and Michne 1993). Releases from such events seem to be small,

based on information available to date. The Department of Energy (DOE) funded research from the early 1970s in marine radio-chemistry, waste-form engineering, deep-sea biology, and physical oceanography through the Sandia National Laboratory in Albuquerque, NM. Principally a DOE weapons laboratory, most of their experimental work was contracted out to oceanographic institutions, but they maintained a staff of engineers and modelers to work on waste form problems and to assimilate environmental information into sets of coupled models which would calculate radionuclide transfers and fates.

The U.S. effort to assess the feasibility of disposing of high-level radioactive wastes in the deep sea was also part of an NEA-sponsored effort called the Seabed Working Group. Members included marine scientists from Canada, FRG, France, Japan, the Netherlands, Switzerland, the UK, and the U.S. The strategy proposed differed from that used for low-level wastes: instead of canisters being dropped to the seafloor, torpedo-shaped waste containers would be emplanted deep into fine-grained sediments with stable geologic histories and which have a high degree of horizontal stratigraphic uniformity. Numerous preliminary reports on site assessments, environmental data, modeling, etc., were published by Sandia, which are available. A detailed summary of the scientific results was published by the NEA (1984), and the highlights are available in a briefing document (JKA 1985).

Review of both the low- and high-level radioactive waste research efforts suggests that there are some apparent advantages to deep-ocean disposal. The deep ocean offers multiple barriers to the return of radionuclides to man: layers of sediments with great stability and ion exchange capacity, deep water with sluggish currents, and extensive distances from any present activity of man. The volume of the receiving medium is so great that releases are diluted to concentrations that would be well below those considered a threat either to man or resident biota. The deep ocean on the broad expanses of abyssal seafloor, the studies confirmed, is a virtual desert because of minimal natural supplies of organic matter necessary to support potential food resources. Thus, there is no threat that a high concentration would be found within a food fish which could be transferred to man.

The "critical pathways" identified by risk analyses that appeared to present the greatest threat were transportation to port and transportation to site. However, the deep ocean avoids the "not in my backyard syndrome," so common in attempts to identify land-based sites. Nonetheless, the DOE terminated studies of the feasibility of high-level waste disposal in the deep ocean in 1985. Misgivings about the feasibility were said to be related to the difficulty and expense of monitoring sites, recovery of wastes if it were necessary, and the perception that our understanding of deep-sea food chains was inadequate.

1.5.4 Dredged Material Research Program *by Philip J. Valent*

The Dredged Material Research Program (DMRP), authorized by Congress by the River and Harbor Act of 1970, was assigned to the U.S. Army Corps of Engineers in 1971, with research initiated at the Waterways Experiment Station (WES) in 1973, and completed in 1978 at a cost of $32.8 million (Saucier et al. 1978). The DMRP objective was to provide "...definitive information on the environmental impact of dredging and dredged material disposal operations and to develop technically satisfactory, environmentally compatible, and economically feasible dredging and disposal alternatives, including consideration of

dredged material as a manageable resource" (Saucier et al. 1978, p 21). The program developed "...methods of evaluating the physical, chemical, and biological impacts of a variety of disposal alternatives—in water, on land, or in wetland areas—and produced tested, viable, cost-effective methods and guidelines for reducing the impacts of conventional disposal alternatives" (Saucier et al. 1978, p 5). Regarding ocean disposal of dredged material, the Executive Overview (Saucier et al. 1978) noted that "As long as the geochemical environment is not basically changed, most contaminants are not released from the sediment particles to the water," and "Some nutrients such as ammonium and manganese and iron are released in open-water disposal, but in most cases enough mixing is present to rapidly dilute these to harmless concentrations." In the DMRP the deep-ocean disposal option was addressed in only one report, a procedural guide for site surveys leading to disposal site selection (Pequegnat et al. 1981). The DMRP Executive Summary noted (Saucier et al. 1978) that, "Contrary to much public, scientific, and governmental opinion, the deep ocean, when analyzed in a detailed objective fashion, is not everywhere a fragile environment totally unacceptable for dredged material disposal. A significant contract study concluded that, should the economic and technological aspects be favorable, extensive deep-ocean areas are more environmentally acceptable for disposal than are some highly productive continental shelf areas, **especially for contaminated materials**." (emphasis by APWI Project). This DMRP statement is based, in part, on the suggestion in Pequegnat et al. (1981), and restated in Pequegnat (1983), that even after major disposal of dredged material, recolonization of the deep seafloor may be rapid. Gage and Tyler (1991), p 401, disagree with the Pequegnat suggestion, citing other studies showing "...that defaunated deep-sea sediments take a long time to recolonize," but then continue, stating, "It is possible that the disposal of marine dredge spoil will have a minimal impact on the deep-sea benthos if spread over a large area and time scale, and may well form an acceptable alternative site to land disposal" (Gage and Tyler, p 401).

After completion of the DMRP, WES continues research, field demonstrations, and technology transfer efforts addressing environmental effects of dredging, disposal, and/or fill activities. Work by the WES with contaminated sediments, comparing the desirability of upland, wetland, and aquatic disposal, show that upland disposal (i.e., placement of dredged material in a subaerial environment) results in "...drying and oxidizing of the dredged material" accompanied by "...substantial increase in acidity, both from acid rainfall and the oxidation of sulfides and organic material. The acidity can increase the environmental mobility and potential release of metals from the dredged material." "Major areas of environmental concern with upland disposal include effluent quality, surface runoff quality, leachate quality, and lethal and sublethal effects on colonizing plants and animals (Peddicord 1988, p 7). Peddicord (1988), p 43, concluded that "Aquatic disposal, which results in the fewest physicochemical changes, produced the least severe and least persistent impacts while upland disposal, which results in the most physicochemical changes, produced the greatest and most persistent impacts." Engler et al. (1990), p 5, summarized the U.S. Army Corps of Engineers position from DMRP evaluations of environmental effects of dredging, stating that "The first conclusion is that no single placement alternative is most suited for a region or a type of project. Conversely, there is no single placement alternative that can be dismissed as environmentally unsatisfactory due to potential impacts. In other words, from a technical standpoint, there is no inherent effect or characteristic of an alternative

placement method that precludes its consideration before specific site assessment. This conclusion holds true for ocean placement, confined placement, or any other alternative."

1.5.5 MESA/New York Bight Studies *by David K. Young*

The New York Bight is that area of the North American Continental Shelf bounded by the New Jersey and Long Island (NY) coastlines on the west and north and by the shelf break lying 150–180 km on the east (Swift et al. 1985). The apex of the New York Bight, which has received wastes resulting from burgeoning population growth of the New York/New Jersey metropolitan region over the past several hundred years, bears the dubious distinction of being that portion of the North American Coastal Zone most heavily affected by human use (Ketchum et al. 1981). Starting in 1888, waste solids were dumped under permit at six major disposal sites in the New York Bight apex, only 10–15 km from the Hudson-Raritan estuarine systems (Gross 1976a). Swanson (1977) described the annual volumetric waste discharges as including sewage sludge (3.7 million cubic meters), dredged material (4.3 million cubic meters), acid-iron waste (2.0 million cubic meters), and construction and demolition debris (0.5 million cubic meters). These volumes (although no longer dumped in the New York Bight apex) continue to increase with concomitant population growth of the region (see Section 1.3, **Waste Stream Analysis**). As a result of past dumping activities (Gross 1976a, p 29), "...shorelines have been built out, hills on the ocean bottom up to 10 m high have been formed, and the head of Hudson Channel has been filled," and because of intermixing among waste deposits and continued pollutant inputs from drainage runoff, much of the material from maintenance dredging in the New York Bight must be handled as contaminated waste.

The first major studies on the potential environmental impacts of dumping practices in the New York Bight were begun in the late 1960s under funding by the Army Corps of Engineers (Pararas-Carayannis 1973). In 1973, the bulk of federally-funded environmental studies in the New York Bight were shifted to the National Oceanic and Atmospheric Administration's (NOAA) Marine Ecosystem Analysis (MESA) New York Bight Project. A number of reports documenting anthropogenic impacts to the New York Bight environment were published by the MESA project, including an Atlas Monograph Series published by the New York Sea Grant Institute (these documents are listed in the **ASWI Bibliography** of this report). These MESA documents, together with journal articles by NOAA-, NSF-, DOE-, and EPA-funded researchers (e.g., Gross 1976b; Mayer 1982), produced what is probably the greatest body of literature on any ocean-disposal area for solid wastes which exists up to the present time.

During the period that the MESA program concentrated its studies on the New York Bight, a variety of contaminant effects potentially attributable to ocean dumping were documented. These contaminant effects (summarized in Ketchum et al. 1985) included marked reductions in benthic species diversity, occurrences of antibiotic-resistant bacteria, fin rot disease in fishes, and gill-clogging in lobsters. Increased public attention to pollution problems in the New York Bight ensued from real or perceived effects of ocean dumping, such as a sewage-sludge scare in summer 1974 (Soucie 1974), contamination of Long Island beaches by floating wastes in summer 1976 (MESA 1977), and anoxia-induced fish

kills of summer 1967 (Swanson and Sindermann 1979). These examples remain as test case examples of public responsiveness and political ramifications resulting from environmental effects of ocean dumping of wastes in coastal zone waters. In 1977, Congress passed new amendments to the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972 specifically ending ocean dumping of sewage sludge and industrial waste after December 31, 1981. Largely because of stated inabilities of the New York/New Jersey metropolitan region to meet the 1981 deadline, Congress codified an EPA administration decision in the Water Resources Development Act of 1986 which served to move sewage sludge ocean disposal from the New York Bight apex dump site to 106 miles offshore (see Section 1.5.2, **106-Mile Ocean Disposal Site**). As a result of medical debris washing ashore and closure of beaches owing to high bacteria counts in New Jersey coastal waters, Congress passed the Ocean-Dumping Ban Act of 1988, which banned all dumping of sewage sludge and industrial waste after December 31, 1991. Since 1992, as a result of the Ocean-Dumping Ban Act, the disposal of any wastes other than dredged material (regulated by MPRSA, see Section 1.2, **Environmental Regulations**) is no longer permitted in the New York Bight.

1.5.6 Ocean-Flux Studies *by Richard A. Jahnke*

A significant effort is presently underway to develop a quantitative understanding of the vertical flux of biogenic materials in the ocean (Joint Global Ocean-Flux Study). Recently, Jahnke (1990) has reviewed the status of these ocean-flux studies. In general, quantitative estimates of the flux of organic materials to the deep waters and seafloor have been derived from sediment trap collections, seafloor benthic chamber incubations, and pore water diffusive flux calculations. Each of these techniques suffers from a unique set of limitations and inaccuracies, but together they provide a quantitative characterization of the natural flux of biogenic particles to the abyssal ocean.

In general, the overall pattern of biogenic fluxes in the deep ocean follows that of the productivity of the overlying waters. The highest fluxes are observed under the biologically productive waters adjacent to continents and the equatorial divergence areas, and the lowest fluxes are observed beneath the low productivity waters of the central gyres. Sediment trapping studies have also demonstrated that the flux of particles to the deep ocean varies temporally. Variations exceeding factors of 10 to 100 in the vertical flux over time periods of days to weeks have been observed at a variety of deep-sea locations (Lampitt 1985; Deuser et al. 1988; Smith 1989). Overall, these variations are correlated with a slight lag period with variations in biological productivity in the overlying surface waters. However, variations may also be caused by changes in biological grazing rates and characteristics and hydrodynamic events that control lateral inputs (Honjo et al. 1982; Deuser et al. 1988).

Studies of biogenic fluxes to the seafloor have recently been summarized by Jahnke and Jackson (1992). As with the deep-water column fluxes, fluxes to the seafloor also follow the general pattern of surface water biological productivity. Fluxes to the seafloor appear to increase dramatically near continental margins. While some of this increase is undoubtedly due to inputs from the higher biological productivity in the overlying waters, this alone can probably not explain the overall increase. It has been suggested that lateral

inputs significantly augment the vertical flux of biogenic particles to the seafloor in continental margin regions (Jahnke et al. 1990; Anderson et al. in press).

These studies indicate that the natural flux of organic carbon to the abyssal seafloor away from significant continental or equatorial influences is generally between 0.01 to 0.05 mol C/m^2yr. This input probably occurs episodically and thus for short periods (days to weeks), fluxes significantly greater than the annual mean may occur.

The overall magnitude of the fluxes to the deep ocean may be verified through hydrographic studies. Because organic materials that enter the deep ocean are nearly quantitatively remineralized, estimates of deep respiration may be used to constrain overall organic input. Based on ^{14}C age measurements and apparent oxygen utilization estimates, Broecker et al. (1991) have estimated the total organic carbon oxidation rate for the deep Atlantic Ocean to be approximately 9 μmol/l 100 years. Rates of a similar magnitude would be expected for the deep Gulf of Mexico and the North Pacific Ocean. Given the volumes of the individual basins, this value suggests that the natural annual organic carbon input rate is 1.2×10^{13}, 4.4×10^{11}, and 3.3×10^{13} moles C/yr for the North Atlantic, Gulf of Mexico, and North Pacific, respectively.

For comparison, example computations provided in Section 5.3.4 will assess the impacts of isolating one million tons of sewage sludge on the abyssal seafloor. If this waste material is comprised of 30% organic carbon, this input is equivalent to approximately 0.2% of the annual natural loading of metabolizable organic carbon into the deep North Atlantic Basin. Thus, the introduction of this quantity of sewage would not significantly increase the organic loading of the North Atlantic and would have a very small impact on the bottom water oxygen concentration.

1.5.7 Deep-Water, Ocean-Dredged Material Disposal Site off San Francisco, California

by Curtis A. Collins

On August 11, 1994, the EPA formally designated an ocean-disposal site for dredged material which is located about 90 km (50 nmi) west of the Golden Gate Bridge in water depths between 2.5 and 3.0 km (CFR 1994). The site occupies an area of 22 square kilometers. The designation of the site is for a period of 50 years with an interim capacity of 4.6×10^3 m^3 (6×10^6 yd^3) of dredged material per calendar year until December 31, 1996. Site capacity following that date will be determined by a long-term management strategy for dredged material from San Francisco Bay. Disposal operations at the site also depend upon site management and monitoring programs.

Designation of the site followed four years of extensive field studies, public meetings, and review of public comment. Five sites over the continental shelf and slope adjacent to the Gulf of Farallones were evaluated. Because of the proximity of these sites to the Farallones and Monterey Bay National Marine Sanctuaries, a special concern was that disposal neither harm marine life nor modify the environment in the sanctuaries. The field studies (described below) indicated that the selected site was sufficiently far from the Sanctuary that no impact would occur from disposal activities. The site is neither an

important fish nursery nor a preferred fishing area, and use of the site would not harm any threatened or endangered species (EPA 1992c, 1993; DON 1993). [Note: Not surprisingly, bird data was incomplete and no statements could be made of the possible effect of disposal operations on birds.]

Physical studies included year-long deployment of an array of six current meter moorings and five hydrographic surveys of the region (CTD and ADCP measurements) (Ramp et al. 1992; Nobel et al. 1992). Benthic studies included ecological monitoring using a seafloor mapping camera (REMOTS) system and sample collection with a Sandia MK-III boxcorer. In addition to data collection at five sites, transects were made along defined depth contours in Pioneer Canyon and over the continental slope (Jessen et al. 1992a–d; Rago et al. 1992). Epifauna and fish surveys at the sites were conducted by ROV and submersible using photographic techniques, and trawling surveys were carried out by local oceanographic vessels. Marine mammal and seabird activities included a census of seabirds and mammals using shipboard observers during oceanographic cruises, analyses of historical data collected by the Point Reyes Bird Observatory, and acquisition of June 1991 breeding seasons data.

These studies were effectively augmented by activities associated with ocean disposal of 0.9×10^6 m^3 (1.2×10^6 yd^3) of dredged material from new construction at NAS Alameda and NSC Oakland. Navy studies began in July 1990, and included many of the types of studies described above, but were focused close to the offshore site that was eventually designated as the disposal site. The Navy also conducted studies during disposal operations in fall of 1993; these confirmed previous studies of the dispersal of plumes in the water column and sediment on the bottom.

The site designation includes a three-tiered monitoring program. Guidance for site monitoring tasks is provided by a Site Management and Monitoring Implementation Manual. Disposal vessels are required to maintain printouts from GPS navigation showing transit routes and disposal coordinates. Only one disposal vessel may be present within the dumping target area at any time, and vessels are required to release materials no further than 1000 m from the dumpsite. Observers from the Point Reyes Bird Observatory are required to accompany on all trips (COE 1990a, b, c; EPA 1991b).

2.0 DESCRIPTION AND CHARACTERIZATION OF ABYSSAL ENVIRONMENTS (NORTH ATLANTIC, NORTH PACIFIC, AND GULF OF MEXICO)

2.1 Physical Oceanography of the Abyssal Oceans *by Albert W. Green*

2.1.1 Main Features of Oceanic and Atmospheric Circulation

This section gives a brief overview of the large-scale features of the oceanic circulation. The background is presented in terms of the analogs and differences between the atmospheric and the oceanic general circulation. This leads to a summary of the abyssal circulation and its importance in the waste isolation problem. Refer to Section 5.1, **Abyssal Flows in the northwest Atlantic, Gulf of Mexico, and northwest Pacific**, its subsections and list of references for a more detailed description of the circulation features in the selected ocean basins.

The abyssal circulation is a component of the coupled atmosphere-ocean system. In the most general sense, the energy source for this system is the differential solar radiative heating from poles to the equator. The relative differences in solar heating create distributions of density gradients in the air and the water that produce currents and winds. The rotation of the earth adds complexity to the dynamics of the system through the necessary condition for the conservation of angular momentum, which imposes a tendency for the motions to be along latitude circles (zonal flow). In the atmosphere, this tendency is clear in the prevailing Trade Winds (easterlies), the midlatitude westerlies, and the polar easterlies; this predominantly zonal flow is interrupted by smaller scale events and large-scale convective overturning that contribute to exchanges of air, moisture, and heat between the poles and the lower latitudes.

Although the atmospheric circulation is well documented, the details of the weather (flow and exchange processes) at any given point on the Earth's surface are not reliably predictable for more than a week. The abyssal circulation has been measured at few sites, and the numerical models of global and basin scale circulation do not include vertical and horizontal resolution sufficient to describe detailed features of the abyssal flows; however, these models do appear to give a reasonable rendition of the deep-ocean transports at the scales of the resolvable bathymetry.

The effects of mountains and other topographic features on winds and weather are well-documented; these features block and guide air flow in the lower atmosphere and may tend to have very long-range influences on large-scale circulation features. In contrast with the localized influences of topography on the atmospheric circulation, the oceanic circulation is totally confined by the bathymetric structure. The upper-ocean large-scale circulation is driven principally by the winds, such that the large-scale features of the mid-ocean surface flows are responses to the large-scale wind patterns, i.e., the equatorial current systems are *easterlies* and the midlatitude drift is *westerly*. In the polar and subpolar zones, water and air are cooled by radiative losses, become unstable, and sink to a level of equilibrium, or a boundary. The lower boundary for the atmosphere is the surface of the earth or sea; for the ocean, the abyssal basins are the depths of maximum descent. As the masses of cold, dense fluids increase, they displace the less dense and move toward lower latitudes. At this stage, similarities between atmospheric and oceanic circulation start to diverge.

2.1.1.1 Western North Atlantic Ocean

The Atlantic is the only ocean that is dynamically connected with the strong cooling and sinking processes in Antarctic and Arctic seas. In the northern subpolar regions, surface water cooling with convective overturning occurs in winter months. Relatively warm, salty water moves into the Iceland-Greenland-Norwegian Sea from the south over the Iceland-Færoe Ridge. Some of this water replenishes that lost from the surface by convective sinking. The other fraction appears to flow into the Barents Sea, a marginal basin of the Arctic Sea. Losses of latent and sensible heat to the atmosphere and space force intensive convection throughout these subpolar seas; large amounts of cold water are formed and displace the water that was previously in the lowest layers. This build-up of cold water mass sets up density and pressure distributions that create intense currents; the flows break the confinement by the basins via natural seafloor valleys and move southward into the abyssal North Atlantic via the Denmark Strait. This current moves southward to a confluence with water generated in the Labrador Sea and the overflows from the Iceland-Færoe Ridge that have moved through transverse faults in the mid-Atlantic Ridge. This combined southward flow is deflected by the Earth's rotation (Coriolis force). Response to this force causes this flow to move along the North American Continental Slope, around the Newfoundland Ridge, and into the western Sohm Abyssal Plain. In this region, vertical mixing is intensified as a well-defined Deep Western Boundary Current (DWBC) forms along the continental slope. In the Sohm basin, the Arctic waters encounter those from the main source of abyssal water (Antarctic Bottom Water), the Antarctic/Weddell Sea. The scant collection of near-bottom current measurements reveal that the region is relatively energetic and variable. In this zone, the principal source of flow energy and variability is the Gulf Stream system, which is the source of large eddies that may penetrate to the bottom. In considering probable sites for waste isolation, this region of the abyssal flow would not be acceptable due to expectations of rapid dispersion of dissolved and suspended matter into the water column. The DWBC has been measured in few locations, but the evidence from the measurements and predictions of models indicate that the DWBC width ranges from about 100 km to 400 km from the continental slope. The DWBC is overshadowed by the Gulf Stream and the complex system of eddies. Generally, for reasons of operational reliability and waste isolation, high-energy regimes such as this should be avoided.

Antarctic Bottom Water (AABW) covers the Hatteras and Nares abyssal plains. This water is colder and slightly less salty than the water lying over it (North Atlantic Deep Water, NADW). The AABW that occupies the bulk of the first kilometer of the water column above these plains is virtually homogeneous; consequently, the static stability is low. This condition permits vertical mixing with no resistance by density stratification; buoyant plumes of substances less dense than the surrounding AABW could rise high in the water column before mixing, and stratification could inhibit vertical motion. The spreading of contaminants could be augmented by concurrent high-energy flows; thus, it is critical to select an isolation site with low kinetic energy. The Nares region appears to be best with respect to this criterion.

2.1.1.2 Eastern North Pacific Ocean

The abyssal circulation of the northeastern Pacific Ocean is less energetic than the northwestern Atlantic. The California Current is the dominant surface current; it is weak and shallow in comparison with the Gulf Stream and the Deep Western Boundary Current system. The AABW is the source of the bottom water; consequently, the static stability is low, slightly lower than the NW Atlantic. The basins adjacent to the continental rise are deeper nearer to the coast. The very limited current measurement data indicate currents are small and are heavily modulated by tidal oscillations. Details of the abyssal bathymetry would be important in selecting an isolation site in this region, since it is more tectonically active.

2.1.1.3 Gulf of Mexico

The Gulf of Mexico is the most energetic of the basins considered. The Loop Current, its meanders, and the large eddies that result from its instabilities are the dominant features of the gulf's circulation. The bottom water of the gulf (Antarctic Intermediate Water) originates north of Antarctica in a broad, subpolar convergence zone. The stability of this bottom water is less than that of the NE Pacific or NW Atlantic. The circulation of this basin has been modeled intensively and in detail, but few observations of the abyssal flows have been made. Extrapolations from the observations and models indicate that currents at abyssal depths are related to the Loop Current and to the eddy decays/interactions. Dispersion of wastes from a bottom site could be accelerated by the advective and fluctuating flows near the bottom.

2.1.2 Factors Controlling Dispersion of Suspended and Dissolved Materials in the Abyssal Ocean

In this introduction, we have mentioned most of the factors that control the bulk of the dispersion of suspended and dissolved materials (S/DM): kinetic energy of the flow, static stability of the water column, and buoyancy of the S/DM. Ideally, from the standpoint of physical isolation of materials on the seafloor, we would want the following conditions: (a) low-to-stagnant flow (less than 2 cm/s with fluctuations less than 1 cm/s) over the site; (b) strong, stable density stratification of the abyssal water; and (c) waste material with bound water and density greater than the contiguous abyssal water. The first factor could be matched in an isolated abyssal valley with steep sides. The abyssal ocean does not have high static stability in any of the zones chosen for possible waste isolation. The rate and potential bulk density of water released from the waste must be known to get good estimates of buoyant plume dynamics. Obviously, ideal conditions will not be attained, but careful site survey measurements, monitoring of test sites, and detailed modeling of S/DM plumes would quantify many issues that are now only conjecture.

2.2 Geology and Geophysics *by Frederick A. Bowles*

2.2.1 Introduction

This section presents a brief geological and geophysical description of the ocean basins adjacent to the continental U.S. and adjacent areas of Canada to familiarize the reader with the major characteristics of each basin (physiography, sediment transport, sediment type, sediment thickness, seismicity, etc.). As an aid to readers not acquainted with marine geology and geophysics terminology, a short glossary is provided (Appendix A). Words that are included in the glossary will appear italicized in the text.

2.2.2 Plate Tectonics Overview

The theory of global plate tectonics embraces the concepts of continental drift and seafloor spreading. The essential idea of plate tectonics is that the entire surface of the earth consists of rigid, thin, undeformable plates (Fig. 2.2.2-1) whose movements amount to a few centimeters per year. The boundaries of the plates are *mid-ocean ridges, marginal trenches, rifts, and fracture zones* (i.e., zones of shearing motion as plates move past each other). At mid-ocean ridges, molten rock (magma) rises to the surface, solidifies, and is pushed aside when new magma rises. Mid-ocean ridges are, then, centers for seafloor spreading where new seafloor is created, and are called "divergent" or "constructive" plate margins. Since the size of the earth is not changing, old seafloor is consumed at "convergent" or "destructive" plate margins. Usually, one plate overrides another with the lower plate gradually pushed down or "subducted" into the earth where it undergoes melting (i.e., it is consumed). Such margins are usually represented by deep-sea trenches (subduction zones) and associated arcuate chains of islands (island arcs) that form near the edge of the overriding plate. At plate boundaries where *oceanic crust* converges with *continental crust* (e.g., west coast of South America), a deep-sea trench and elongate mountain chain (cordillera) is formed. A third type of convergence occurs when two pieces of continental crust collide (e.g., when the subcontinent of India drifted into the underside of Asia). The result is the crumpling and melding of the crusts into mountains (i.e., the Himalayas). Whatever the nature of the plate boundary, it is always the site of strong seismic (earthquakes), volcanic, and tectonic activity. In contrast, the interior portions of the plates are essentially aseismic, i.e., there is no intra-plate seismicity.

Some continental margins are also plate boundaries and are termed "active margins." Such is the case for the west coast of the U.S. which is experiencing tectonic deformation and volcanism due to its interaction (subduction and shear) with the Pacific Plate. In contrast, on the east coast of the U.S., the continental crust and oceanic crust remain fixed relative to each other. As a result, the continent and ocean basin move (westward) as a unit with the result that the margin is relatively undisturbed by tectonic processes, other than sinking and accumulating thick sequences of sediment. Margins of this nature are termed "passive margins."

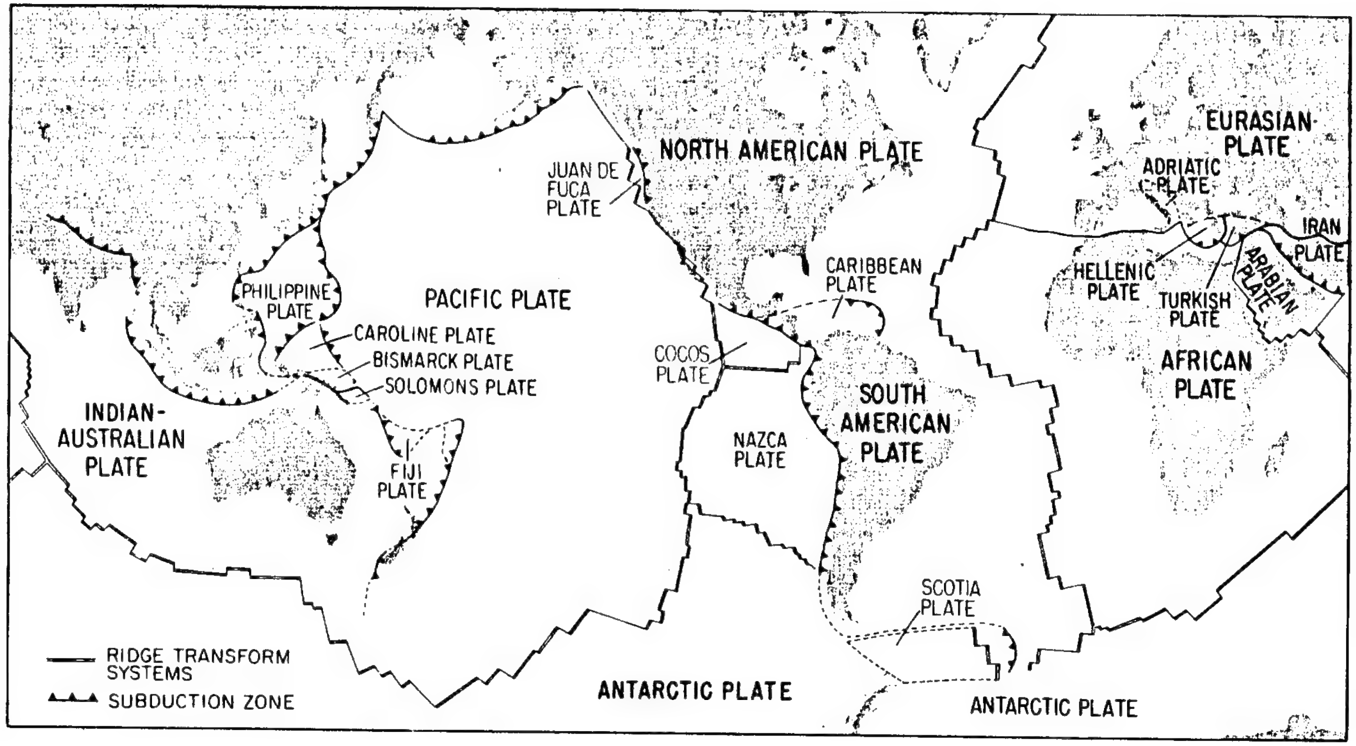

Fig. 2.2.2-1. World map showing boundaries of crustal plates (from Dewey, 1972).

2.2.3 Western North Atlantic Basin

2.2.3.1 Physiography

Except for a narrowing at Cape Hatteras, the *continental shelf* of the eastern U.S. is relatively broad from Florida/Georgia to Delaware/New Jersey where the shelf broadens, becoming very wide off the New England and Nova Scotia coasts (Fig. 2.2.3-1). Off northern Florida, the shelf width begins to decrease until it is almost nonexistent off southernmost Florida.

A steepening in gradient marks the edge of the shelf and the beginning of the *continental slope*. For most of the east coast, the continental slope gradient is relatively uniform. Off southern Georgia and along Florida, however, the continental slope is interrupted by a large terrace called the Blake Plateau that is nearly 300 km wide and 750–1000 m deep. The Blake Plateau is part of an extensive province of shallow banks and plateaus that includes the Bahama Banks. To the north the plateau narrows, shoals, and pinches out in the vicinity of Cape Hatteras. The seaward edge of the Plateau is marked by a steep escarpment (20°), which contrasts dramatically with the gentle upper slope (2–4°) that marks its western boundary.

At the base of the continental slope is the *continental rise*, a broad, gently sloping feature that gradually transitions into the deep basin. Off Georgia the rise detaches from the slope and forms a large sedimentary deposit called the Blake-Bahama Outer Ridge.

Most of the seafloor of the western Atlantic basin is occupied by the Bermuda Rise, an elongate topographic arch (2000 × 1000 km) rising approximately 1 km above the surrounding ocean basin. Near the center of the Rise is the Bermuda Pedestal and the island of Bermuda. Except for a province of *abyssal hills* to the southeast, the Rise is all but surrounded by areas of smooth, flat seafloor called the Sohm, Hatteras, Nares, and Blake-Bahama Abyssal Plains. The slope of an *abyssal plain* surface is roughly 1:10,000 and, unlike the Bermuda Rise which is characterized by small seamounts and rough topography, rarely do any bottom features pierce the surface of these plains. The chief exceptions to this are the New England Seamount Chain and Corner Rise that occur north of the Bermuda Rise.

2.2.3.2 Sediment Transport

The continental shelf areas are the initial dumping site for material eroding from the continents. The sediments arrive there by way of rivers and streams and the coastal erosion by wave action. The eroded sediment is then distributed by shelf currents, with deposition on the continental slopes and rises, by the process of seaward migration of the finer component while in suspension (Schubel and Okubo 1972). The process of sediment distribution on the slope is one of downslope transport of the coarse (*sand* and *silt*) shelf sediment by *current traction* and gravity-induced mechanisms (*slumps, turbidity currents*) with concurrent transport of finer material (*clay*) in suspension. Material that reaches the rise is subsequently redistributed and deposited by bottom currents (i.e., the Western Boundary Undercurrent) that follow the depth contours (isobaths) of the rise.

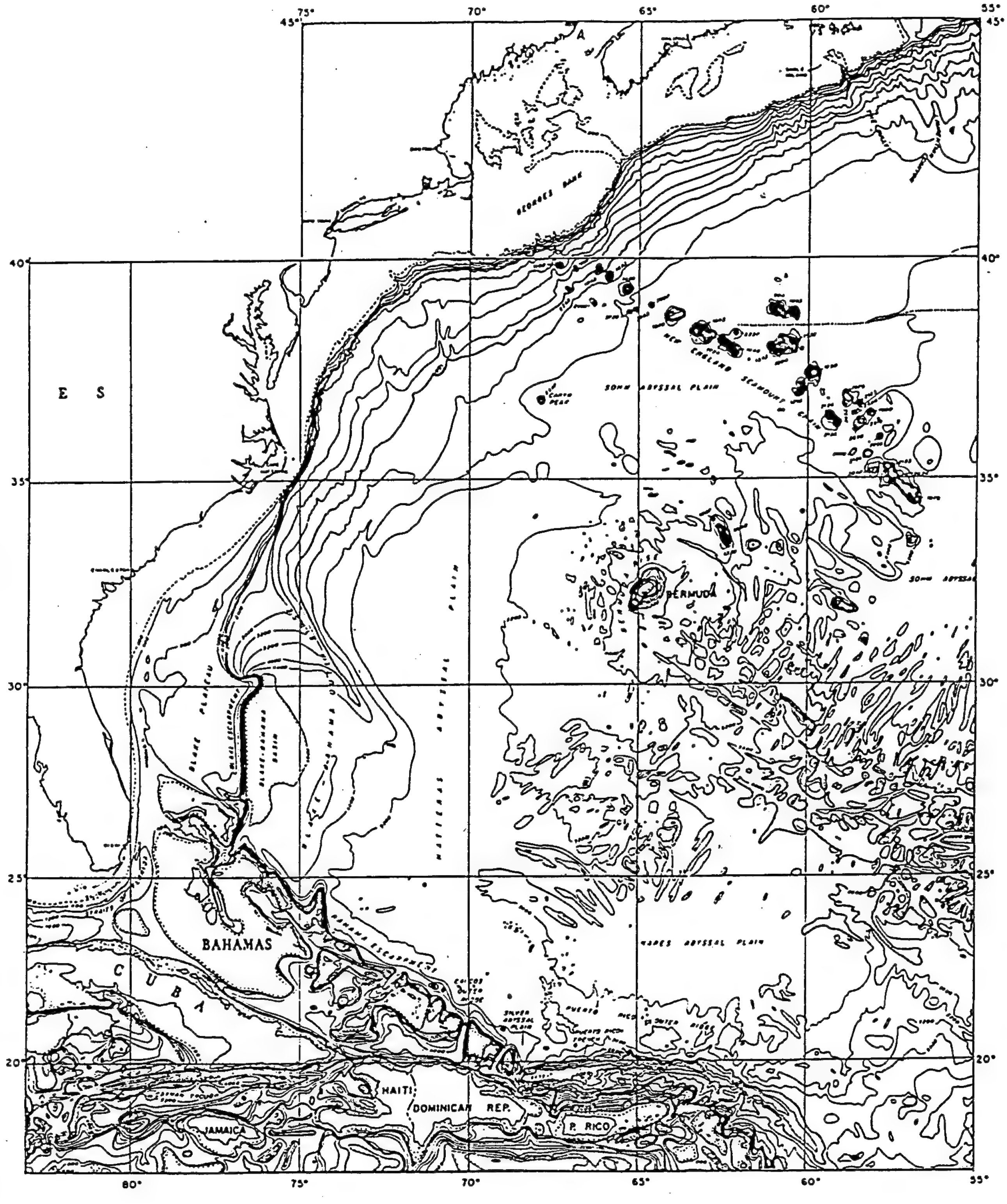

Fig. 2.2.3-1. Bathymetric-physiographic map of the western North Atlantic. Contours in meters.

Turbidity currents are primarily responsible for transporting coarse shelf sediments to the deep-abyssal plains. *Submarine canyons*, incised into the continental slope, act as conduits from the shelf edge to the plain. Once a turbidity current leaves the canyon it spreads out horizontally across the deep-basin floor depositing a blanket-like layer of sand and silt (*turbidite* layer). Over time, turbidity currents have filled in the deeper parts of basins, surrounding the high-standing topography with flat-lying turbidite layers that gradually build up and bury all but the highest peaks. In this way, turbidity currents have created abyssal plains, some of the smoothest, flattest surfaces on Earth. Because turbidity currents are periodic events, they are spaced by periods of slow, *pelagic deposition* which show up in the *stratigraphic record* as layers of fine-grained sediment interbedded with the coarse, turbidite layers.

The Bermuda Rise, because of its elevation, cannot experience turbidity currents. Moreover, it is far from continental areas. As a result, marine currents and wind deliver most of the *terrigenous sediments* to the rise while slow settling of biological organisms from the surface waters furnish *carbonate sediment* (*foraminifera tests* and *coccoliths*) to the Rise. Deposition immediately around the base of the Bermuda pedestal, however, differs significantly from the pelagic deposition that normally characterizes the Bermuda Rise. Around the pedestal, mass transport mechanisms (*slumps*, *debris flows*, etc.) have constructed an extensive *archipelagic apron* consisting of thick deposits of coarse-grained *volcanogenic sediment* (Bowles 1980).

Wind-transported (eolian) sediment, derived from continental areas (and volcanic eruptions), adds a terrigenous component to the pelagic sediments of the deep sea that is latitudinally constrained by global wind patterns. Thus, eolian transport is important mainly in the equatorial regions of the Atlantic where the trade winds erode *clay minerals* and sand from dry regions in north Africa.

Icebergs, like turbidity currents, also transport coarse material (as well as fine) far out to sea. As the ice melts, the sediment load is dropped. Obviously, this is a phenomenon for high-latitudes, and the present-day normal limits of drift ice do not extend much beyond the southern tip of Newfoundland. During the last ice age, however, the limit of icebergs extended farther south to 40°N, or roughly a line between Philadelphia and Madrid.

2.2.3.3 Sediments

As a general rule, the *textural* distribution of marine sediments is largely controlled by depth and/or distance from source. Coarse-grained sediments tend to be found close to shore where the water is shallow (high energy), and fine-grained sediments are found offshore in deeper waters (low energy). Nevertheless, although coarse-grained sediments characterize the continental shelf, there is no general trend of decreasing sediment-grain size seaward across the shelf. Instead, the typical shelf bottom-sediment chart resembles a patchwork quilt (Shepard 1973). Much of the sand on the eastern continental shelf, particularly that found on the outer shelf, is relict sediment that remains from the last ice age when sea levels were lower. The distribution of the relict sand is modified by such things as character of the land area (e.g., glaciated versus *coastal plain*), coastal configuration, strength of shelf currents, etc. Thus, the modern sediment cover of the shelf includes sand, silt, and *mud* deposits, any of which may be found on the inner, middle, or outer shelf areas.

Beyond the shelf, on the continental slope and rise provinces, the sediments are mainly fine-grained. The sediments of the upper continental rise are grey-brown *hemipelagic* silty clays that tend to be homogeneous in nature. In contrast, the sediments of the lower rise are well-layered, pure brown silty clays. These layers attest to the removal (winnowing) of fine sediment by *contour currents* in addition to their transport of silt-size sediment from northern source areas (a diagnostic red hue to some of this sediment is indicative of a source area in the St. Lawrence region of Canada).

Abyssal plain sediments are typically brown clays with interbedded sand and/or silt layers, many of which exhibit *graded bedding* (Fig. 2.2.3-2). The turbidite layers are predominantly the result of heightened turbidity current activity during the low-sea-level intervals (glacials) of the Pleistocene. As a consequence of present-day high sea levels (interglacial), modern turbidity currents are infrequent, and most abyssal plain areas are veneered with a thin (10–20 cm) layer of fine-grained sediment. Because abyssal plain seafloors are below the depth at which calcium carbonate readily goes into solution (about 4500 m), these fine-grained sediments are predominantly terrigenous clays.

Most of the Bermuda Rise is above the *calcium compensation depth* (CCD). Hence, the sediments here are a blend of terrigenous clays and fine-grained, *biogenic* carbonates (i.e., calcareous clays, calcareous oozes).

Coarse, disseminated debris is found concentrated in zones within the sediment deposits north of 40°N. As discussed above, this debris is a consequence of ice transport. The zones correspond to the Pleistocene glacial epochs when ice-rafting of sediment was enhanced by the cooler climatic conditions and the southward encroachment of polar water masses.

2.2.3.4 Sediment Thickness

Typically, the accumulation of sediments in the ocean basins thickens as one moves away from the mid-ocean ridge crests and towards the continents. In the Atlantic sediments, thicknesses beneath the shelf and upper slope areas are on the order of 10–15 km whereas those on the lower slope and upper rise are 5- to 10-km thick (Fig. 2.2.3-3). The lower rise sediments are roughly 3- to 5-km thick. These thin and transition smoothly into the flat-lying sediments to the abyssal plain areas where 1–2 km of unconsolidated to semiconsolidated sediment overlie the *crystalline basement rocks*. Sediment accumulation is comparatively thicker on the northern Bermuda Rise (0.5–1.0 km) than on the southern part (0.2–0.5 km). Farther east, on the exposed flank topography of the mid-ocean ridge, one encounters sediment thicknesses that are typically 0.1 km or less.

It is important to recognize that the sediment thicknesses given above reflect regional trends and that locally (e.g., within fracture zones or on topographic highs) the accumulations of sediments may be substantially different.

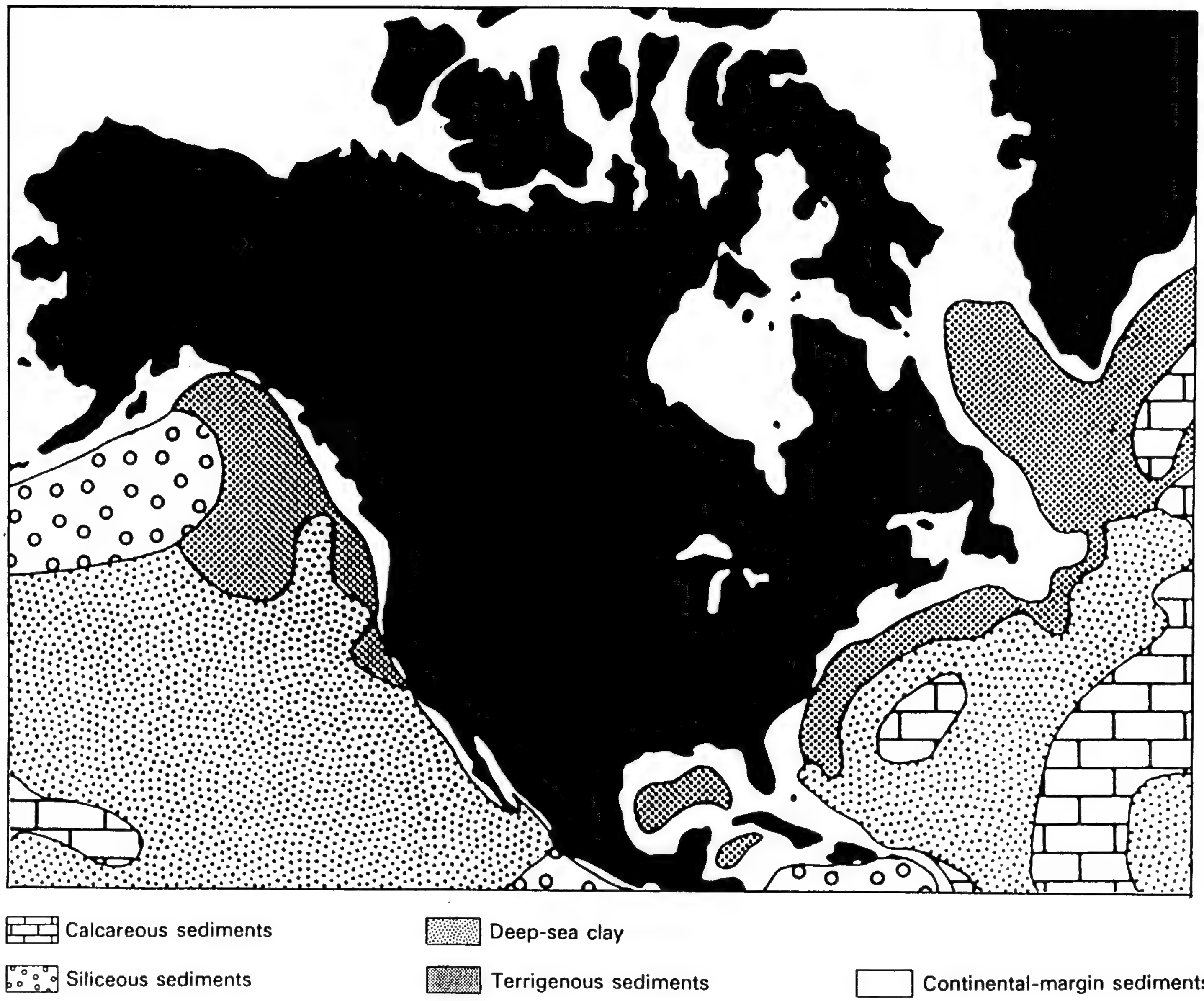

Fig. 2.2.3-2. Distribution of principal types of pelagic sediment on ocean floor (from Jenkyns,1978).

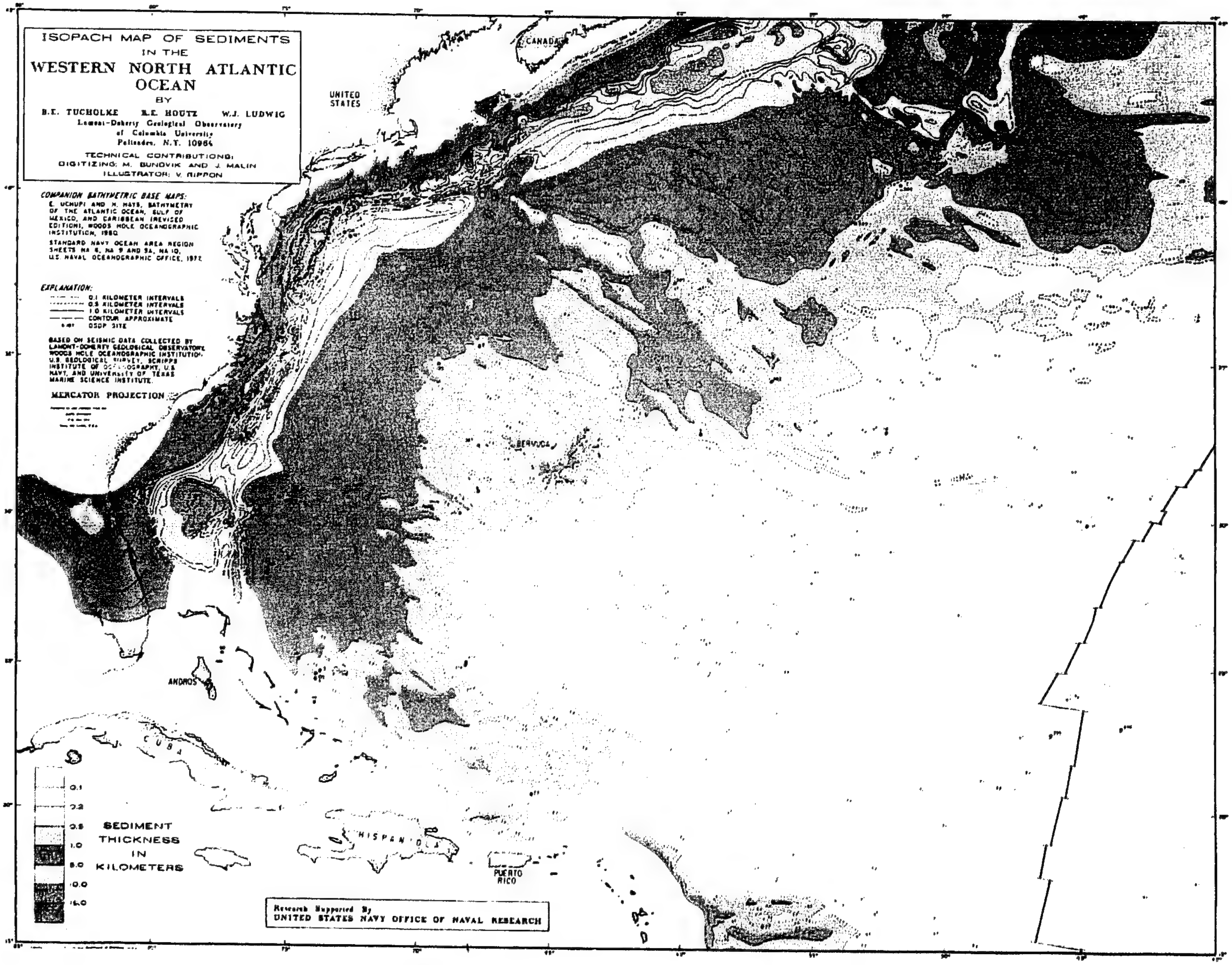

Fig. 2.2.3-3. Map of sediment thickness in the western North Atlantic (from Tucholke et al., 1982).

2.2.3.5 Seismicity

In the North Atlantic nearly all the earthquake (seismic) activity is associated with the mid-ocean ridge running longitudinally down the center of the basin and with the Puerto Rican Trench, both of which are plate boundaries (Figs. 2.2.3-4 and 2.2.2-1). As discussed, movement of the earth's crust along plate boundaries accounts for nearly all the world's earthquake and volcanic activity. Because none of the continental margins adjoining the Atlantic are plate boundaries, the margins of the Atlantic, and the interior of the North American Plate as a whole, are largely aseismic.

2.2.4 Eastern North Pacific Basin

2.2.4.1 Physiography

The Atlantic and Pacific continental margins are shaped by different forces. As a result, the continental margin off the Pacific coast of the U.S. differs from the east coast in several respects. It has, for the most part, a narrower continental shelf area with a steeper continental slope and poorly developed continental rise (Fig. 2.2.4-1). In fact, most of the continental rise stretching from the Strait of Juan de Fuca to about Los Angeles is formed by a series of *deep-sea fan* deposits (Nitinat, Astoria, Delgada, and Monterey) which, as yet, have not developed into the classic rise morphology found on the Atlantic side. One probable reason for this is the absence of a contour current, which is a major factor in shaping the east coast continental rise. There are no fan or incipient rise deposits off southern California. Here, the shelf is incised by a series of elongate basins that parallel the coast and trap sediments moving across the shelf. Moreover, the region is arid, and drainage of the hinterland is reduced.

From about the Mendocino Fracture Zone (40°N) southward along the U.S. and Mexican coasts, the seafloor of the eastern North Pacific is predominantly a province of abyssal hills. In form, the hills are usually elongate features, 1- to 10-km wide, with relief in the 50- to 1000-m range and slopes of 1–15°. The hills, which are sediment covered, represent the surface expression of topography produced by seafloor spreading. In addition, the seafloor spreading process has resulted in a series of east-to-west-trending fracture zones that slice through the abyssal hill province. Although abyssal hill and fracture zone morphologies are also found in the western Atlantic, they only occur between the mid-ocean ridge crest and the eastern edge of the Bermuda Rise.

The only abyssal plain province in the eastern North Pacific occurs north of the Mendocino Fracture Zone. Here, all but the tallest abyssal hills are buried beneath the sediments of the Tufts, Alaskan, and Aleutian Abyssal Plains. Near the Oregon/Washington coasts, however, the abyssal plain sediments lap onto the high-standing topography of the Explorer-Juan de Fuca-Gorda Ridge complex. The area between the ridges and the Oregon/Washington coasts is occupied by the Nitinat and Astoria Deep-Sea Fans.

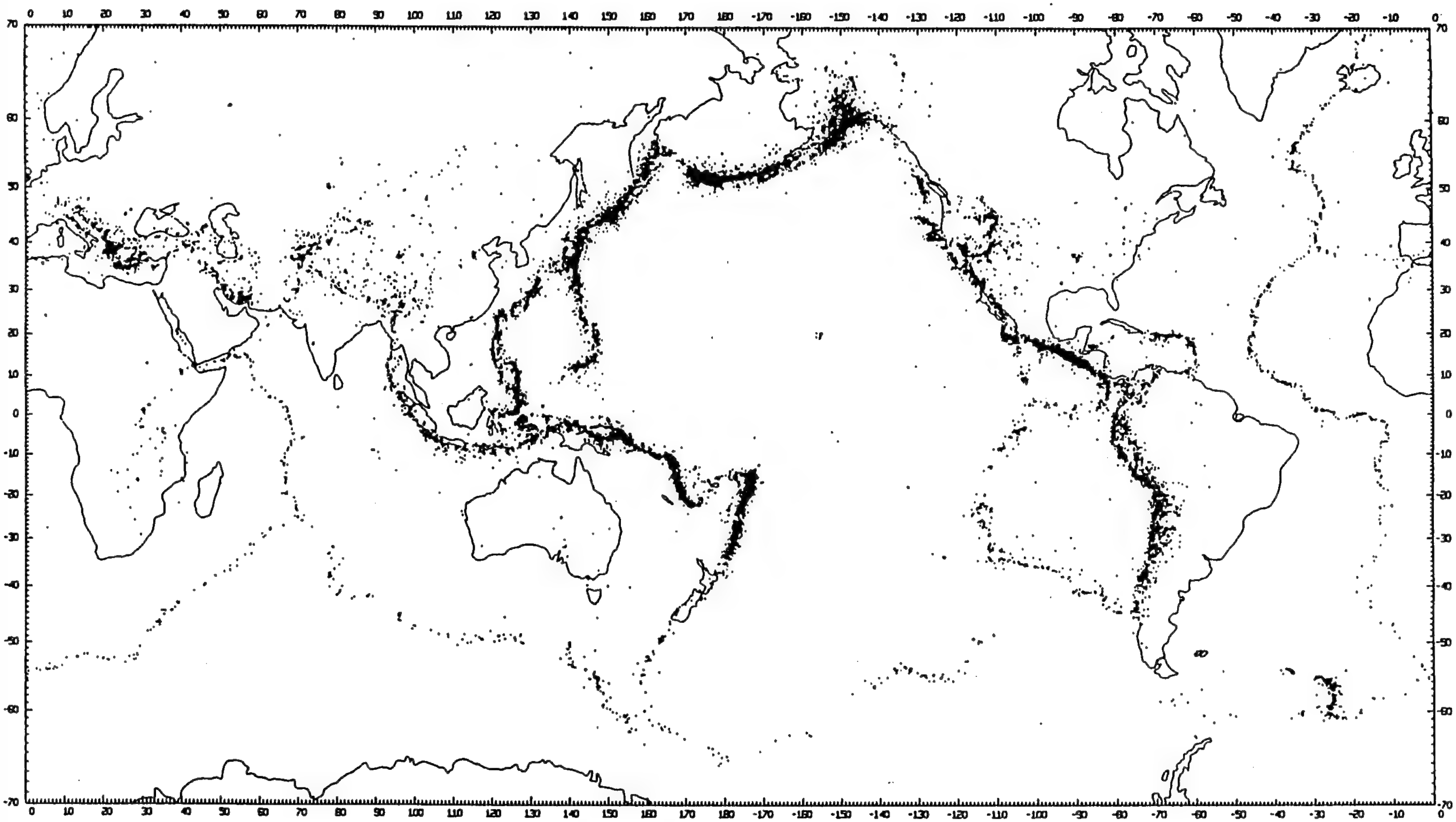

Fig. 2.2.3-4. Locations of shallow-focus earthquakes, depths 0 - 100 km, during 1961-1967 (From Sykes, 1972).

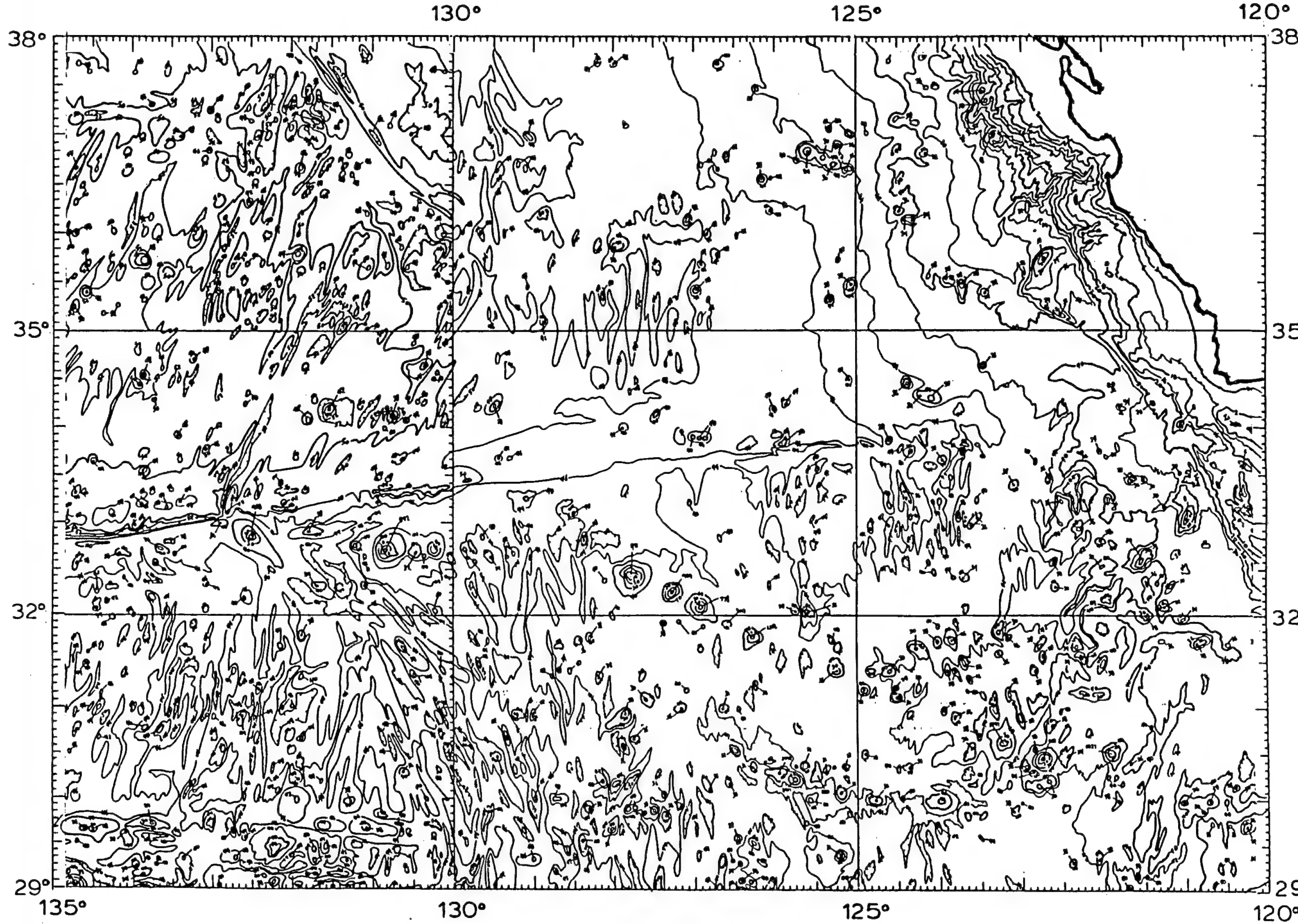

Fig. 2.2.4-1. Naval Oceanographic Office World Relief Map, NP-9, of the eastern North Pacific off southern California. Contours in meters.

2.2.4.2 Sediment Transport

The same sediment transport processes that characterize the western Atlantic basin are also active in the Pacific. Turbidity, currents, and slumping feed the sediments to the deep-sea fans located at the base of the continental slope. As the fans continue to build, they are gradually encroaching westward into the abyssal hills, which is dominantly a province of pelagic sedimentation with the sediments being transported by currents and wind. Indeed, studies of North Pacific *red clays* reveal that they consist mainly of windblown debris derived from fine-grained glacial deposits (loess) in North America and Asia (Heath 1969; Bryant and Bennett 1988). Near active oceanic margins with their associated volcanoes, wind transport is responsible for the occurrence of volcanic ash (tephra) in the offshore deep-sea deposits.

Turbidity currents are largely responsible for the morphologies of the abyssal plains north of 42°N. The Alaskan Abyssal Plain is fed by turbidity currents that originate in the glacial troughs of the Canadian and Alaskan shelves and travel the deep-sea channels that cross the plain. Sands and silts eventually find their way to the Tufts Abyssal Plain via Cascadia Channel (Fig. 2.2.4-2), which is connected with the submarine canyons of the continental slope off Washington. Because these plains are situated in the high latitudes, a component of their coarse sediment is derived from ice transport. This component is readily identified by the fact that it is largely disseminated in the sediments rather than confined to discrete, sharply defined beds as in the case of coarse-grained turbidite layers.

As in the Atlantic, modern sedimentation on these plains is pelagic due to the infrequency of turbidity currents at the present time. The Aleutian Abyssal Plain has not received turbidity currents for approximately 32 million years (Scholl and Creager 1973, p 11). Consequently, it is covered by a thick layer (100 m) of pelagic clay and is considered to be a relict or fossil turbidite plain.

2.2.4.3 Sediments

The Pacific shelf sediments are comprised largely of sands and coarse silts. The narrow, high-energy environment of the shelf transports the finer materials in suspension and deposits them on the continental slope and in the deep basin. Fine-grained sediments not only cover the deeper parts of the North Pacific Basin, but the abyssal plains provinces in the northeast as well. Further, in the abyssal plains provinces, numerous sand/silt (turbidite) layers occur beneath the surface veneer of fine sediment. Such is the case, as well, for the deep-sea fans at the base of the continental slope. However, the chances of encountering surface sands and silts here are greater because of the proximity of the fans to their source areas.

Except for ridge areas, such as the Juan de Fuca, and seamounts that rise above the CCD (about 4500 m), the deep North Pacific is devoid of carbonate sediments north of about 10°. Instead, the fine-grained sediments found here are brown to reddish-brown terrigenous clays. On the other hand, biosiliceous material (diatoms, radiolaria) tend to be preserved in areas that are deeper than the CCD. Biosiliceous materials contribute

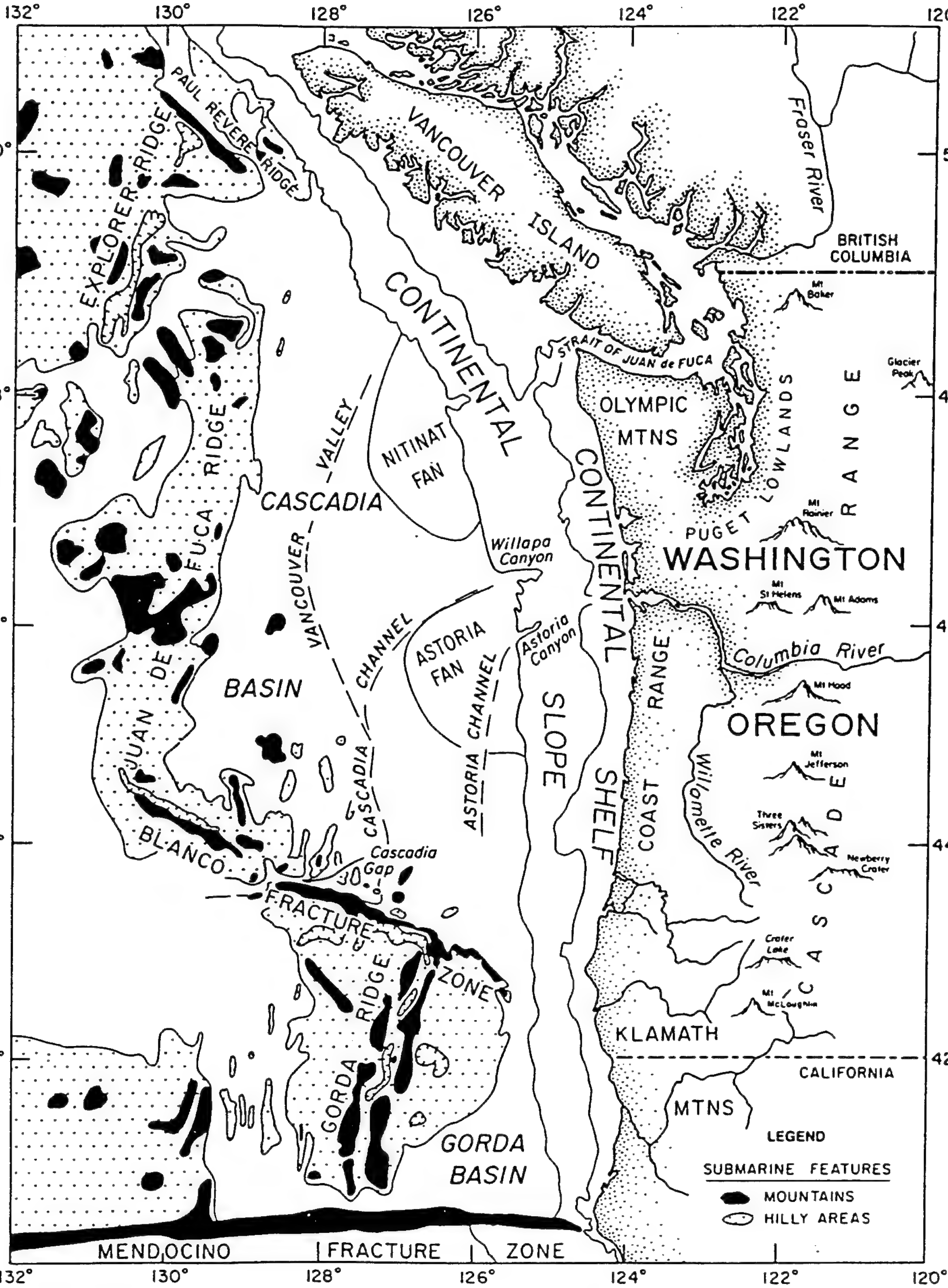

Fig. 2.2.4-2. Physiography of the Juan de Fuca Plate off the Washington and Oregon coasts (Ducan and Kulm, 1989).

significantly to sediments that accumulate beneath biologically productive surface waters, e.g., north of about 40°N, south of about 15°N, and along the California coast (due to *upwelling* of cold, nutrient-rich water).

Modern icebergs do not penetrate south of the Aleutian Islands. During the Pleistocene, however, icebergs traveled as far south as Vancouver (Fairbridge et al. 1966, p. 674). Consequently, the sediments of the Gulf of Alaska contain a coarse-grained component that is ice-rafted.

In the Pacific, a substantial amount of material is derived from volcanoes, especially those near active plate margins. High concentrations of volcanogenic ash, or tephra, are found in the sediments of the Gulf of Alaska and off Central America.

2.2.4.4 Sediment Thickness

With a few exceptions, the thickest accumulations of sediments are found mainly at the foot of the continental slopes, in the bottoms of the trenches, and beneath the abyssal plains in the northeast (Fig. 2.2.4-3). In the open-ocean basin, slow (pelagic) sedimentation has resulted in a thin accumulation of sediment.

In the eastern North Pacific, the thickest accumulations of sediment are found off Vancouver and the northwestern U.S. where the complex of spreading ridges and fracture zones (Fig. 2.2.4-2) forms barriers to the seaward dispersal of terrigenous sediments. This has resulted in a sediment accumulation of 1600 m near the base of the continental slope with the sediment rapidly thinning (50–100 m) westward onto the flanks of the ridges (Fig. 2.2.4-3). Comparable sediment accumulations characterize the deep-sea fan areas along the California borderland. Farther south, however, sediment thicknesses decrease to a few hundred meters because of the reduced sediment supply.

Away from the continental margin, in the abyssal hill province, the regional sediment thickness is 100 m or less; locally the sediments may be somewhat thicker in lows and thinner on highs. In the Gulf of Alaska, the sediment deposits achieve thicknesses of up to 800 m near the Aleutian Trench and even greater beneath the deep-sea fans adjacent to the Alaska margin. Away from the margin the sediments thin. Thicknesses on the distal part of the Tufts and the Aleutian Abyssal Plains are less than 200 m.

2.2.4.5 Seismicity

Earthquakes and volcanism are hallmarks of the Pacific basin. Most of the Pacific basin is rimmed by deep-sea trenches which, as previously noted, are plate boundaries where subduction is occurring. Consequently, nearly all the earthquake and volcanic activity (seismicity) occurring in the Pacific is associated with the marginal trenches and, as evident in Figure 2.2.3-4, there is virtually no seismic activity away from the trench areas. Intraplate volcanism accounts for a small percentage (10% or less) of the volcanic activity in the Pacific, even though a large portion of the seafloor is comprised of seamounts having volcanic origins.

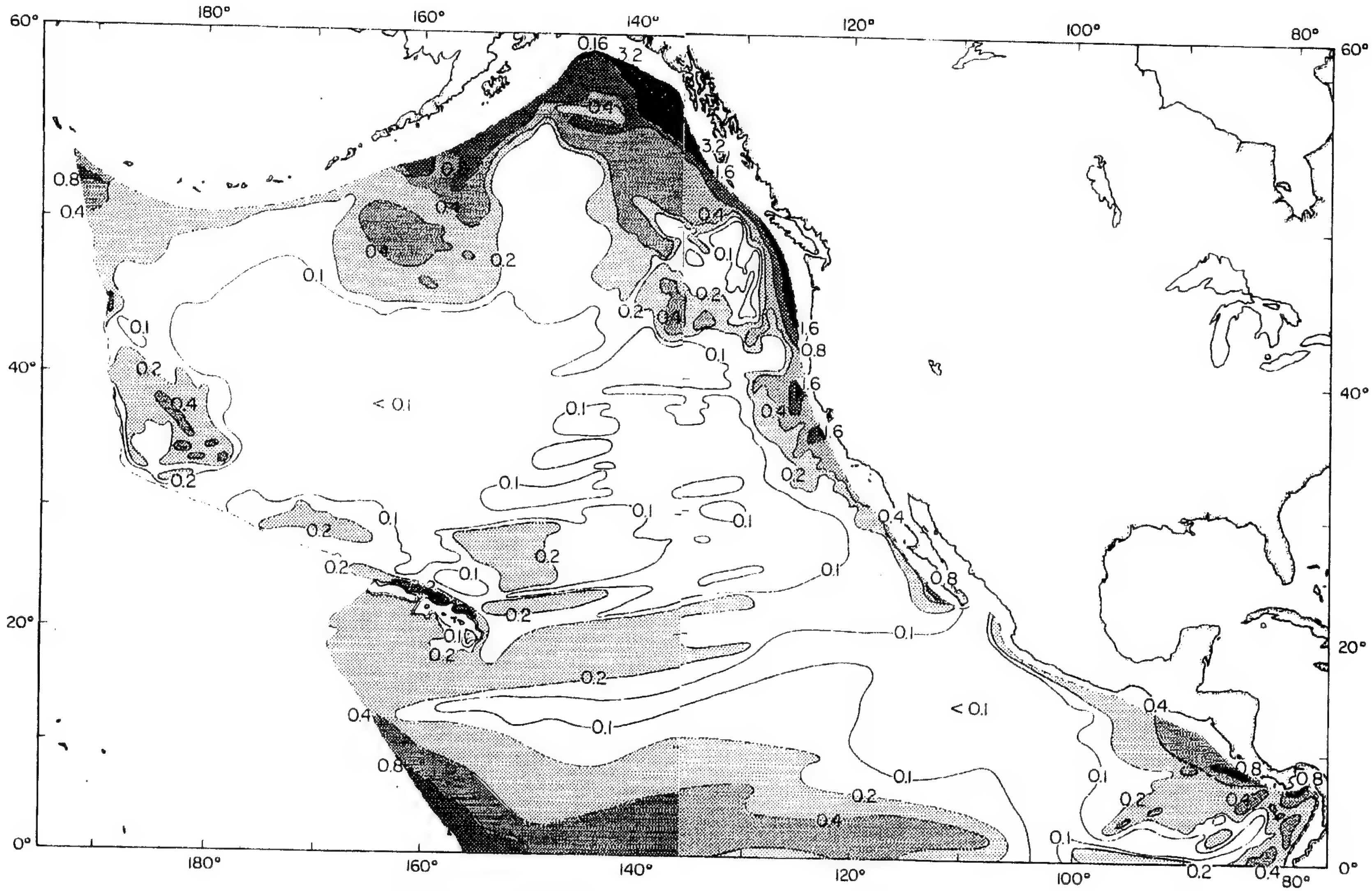

Figure 2.2.4-3. Map of sediment thickness in the eastern North Pacific (from Winterer, 1989).

2.2.5 GULF OF MEXICO

2.2.5.1 Physiography

The Gulf of Mexico is a small, semienclosed oceanic basin that is rimmed by wide continental shelf areas (up to 170 km) except off southeastern Mexico where the shelf is less than 13 km wide in some places (Fig. 2.2.5-1). The preeminent feature of the shelf area along the southern U.S. coastline is the Mississippi River delta. In the area of the delta the shelf narrows due to encroachment by the delta across the shelf.

The continental slopes off the Florida and Campeche shelves begin as gradual descents to the deep basin, but the gradients decrease in the middle portions of both slopes to form terraces. Seaward of the terraces, however, the gradients increase sharply becoming some of the steepest submarine slopes in the world (up to 45°). These precipitous slopes contrast strikingly with the hummocky low-angle slope off Texas and Louisiana. The complex morphology of the Texas-Louisiana slope is due to the presence of numerous *salt domes* (*diapirs*) formed by upward migration (diapirism) from underlying salt deposits (Fig. 2.2.5-2). A similar province of hummocky topography, Campeche Knolls, is situated directly south in the Bay of Campeche and is also attributed to salt diapirs.

The East Mexico Slope consists of linear, symmetrical, ridge-like structures that have a maximum relief of 500 m. The ridges are thought to represent *folds* that have resulted from massive gravity sliding triggered by regional uplift. The Rio Grande and Veracruz Tongue represent slopes that are complex transitional areas between the salt provinces off Texas and Campeche and the ridges off Mexico.

Off the Mississippi Delta the actual (structural) continental slope is buried beneath the sediments of the Mississippi Fan, a thick deposit of sediments resulting from the outflow of the Mississippi River. The deeper, *distal* portions of the fan merge with the Florida Abyssal Plain to the southeast and the flat floor of the Sigsbee Abyssal Plain on the southwest. The grouping of knolls (Sigsbee Knolls) in roughly the center of the plain are attributed to salt diapirism.

2.2.5.2 Sediment Transport

Slumping, sliding, and turbidity currents are the dominant mechanisms by which the Mississippi Fan sediments are dispersed to the deep parts of the Gulf of Mexico. Mass movement of sediment by slumping and sliding prevails on the upper fan where the average gradient is 1°. The fan surface here is irregular and cut by an *unleveed* channel. Although a smoother and less steep surface, the middle fan is also made up of extensive slumped material. However, the existence of a massive complex of filled channels with natural *levees* attests to the increased importance of turbidity currents in constructing this part of the fan. Geophysical profiles show interbedded units of continuous reflectors that are interpreted to be turbidites (Bryant et al. 1991). The lower, distal fan is very smooth with a gently sloping surface merging with the more flat-lying deposits of the Sigsbee Abyssal Plain.

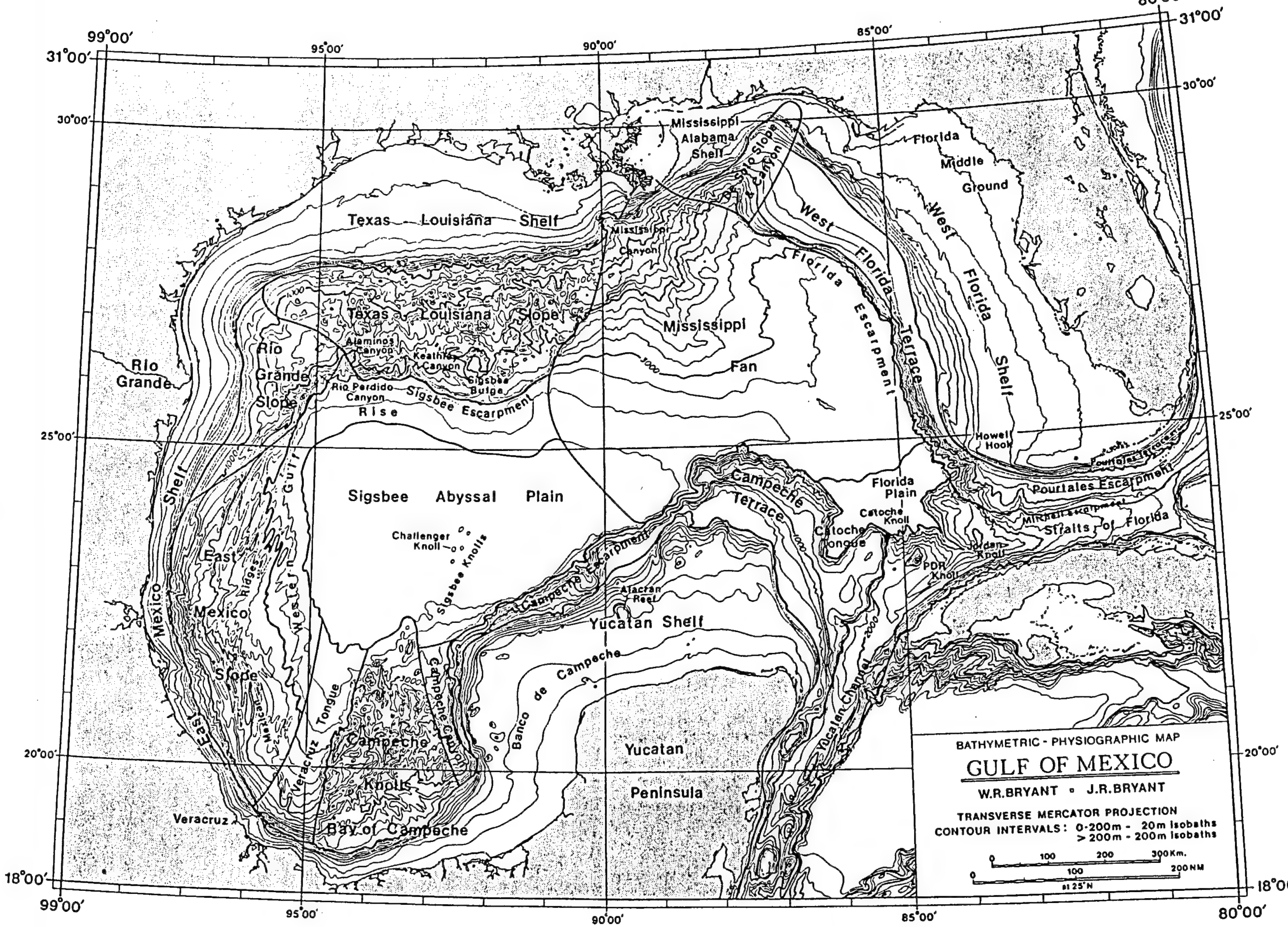

Fig. 2.2.5-1 Bathymetric-physiographic map of the Gulf of Mexico (from Bryant et al., 1991).

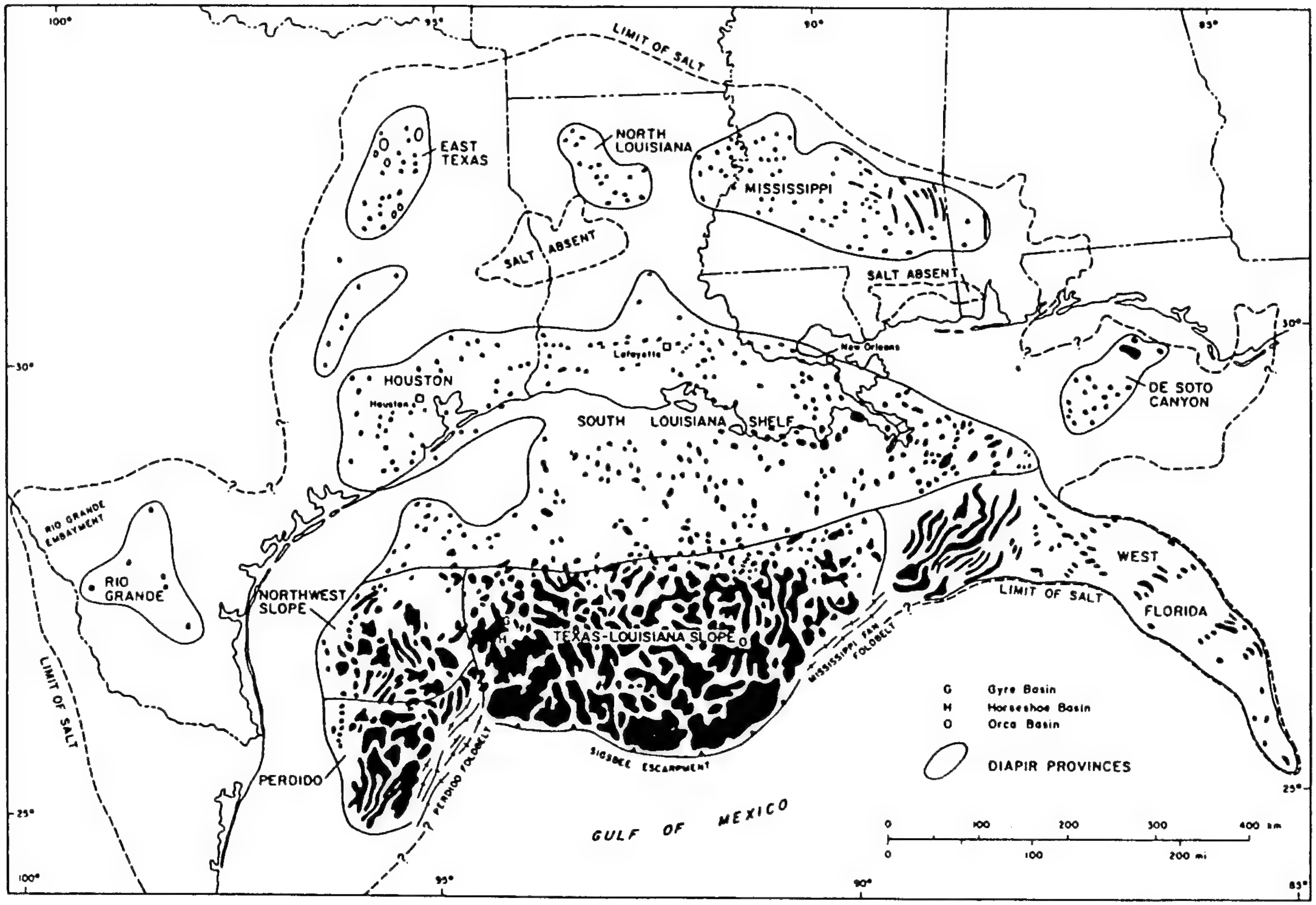

Fig. 2.2.5-2 Salt diapir provinces of the northern Gulf of Mexico (from Ewing, 1991).

Turbidity currents are the primary agents responsible for constructing the lower fan as well as the abyssal plain. Thus, it is impossible to tell, on the basis of sediment characteristics and surface morphology, exactly where the fan ends and the plain begins. It would be wrong, however, to assume from this that Mississippi River outflow is the sole source for the sediment in the abyssal plain. The Rio Grande River furnished large amounts of sediment to the gulf during the Pleistocene (Bouma 1972) as did other rivers. Turbidity currents carrying this sediment undoubtedly reached the Sigsbee Abyssal Plain by way of other canyon systems situated around the periphery of the western gulf. These canyons, being largely Pleistocene features, are presently inactive according to Bouma (1972).

Shelf currents are responsible for distributing sediments over the continental shelf areas and out to the shelf/slope break. Mass movement (e.g., slumping, sliding, turbidity currents) and current traction transport the coarser shelf sediments onto the slope and into the deep basin. Fine sediment is continually carried in suspension and dispersed by currents throughout all the environments of the gulf (shelf, slope, deep basin).

Along the east coast of Mexico, the offshore ridge system has prevented the movement of coarse terrigenous sediments from continental Mexico into the deep basin. As a result, the inner folds are buried while the outer ones remain exposed (Kennett 1982). The salt domes and ridges of the Texas-Louisiana continental slope also act to trap sediment. Thus, the sediments deposited on these slope areas are carried in suspension and slowly deposited.

2.2.5.3 Sediments

As general observations, a veneer of pelagic and hemipelagic fine-grained sediment generally blankets most off-shelf areas of the Gulf of Mexico (Fig. 2.2.5-3). In the deepest parts of the gulf the veneer is underlain by bedded deposits of sand and silt (i.e., turbidites) of Pleistocene age. Compositionally, the shelf and slope sediments of the northern and western gulf are dominantly terrigenous in nature, whereas those of the eastern and southern Gulf are dominantly calcareous (carbonate). Carbonate-rich sediments also dominate topographic highs, such as diapirs and ridges.

The most textural variability occurs on the shelf areas. The inner and middle shelf environments from about Florida-Alabama around to about Campeche Canyon consist primarily of terrigenous sand and mud with the sands generally concentrated in pockets and close to shore. The Florida and Campeche shelves are covered with a thin veneer of mostly carbonate shelly sands and some muds overlying flat-lying limestone *strata*. On the Florida shelf, where the sediment zones for the most part run parallel to the shelf contours, quartz-rich sands dominate the inner shelf while the carbonate sands dominate elsewhere.

Volcanic ash layers are found in the sediments of the western Gulf of Mexico. The ash is derived from volcanic eruptions in Central America and was carried into the gulf by prevailing eastward-blowing high-latitude winds (Kennett 1982).

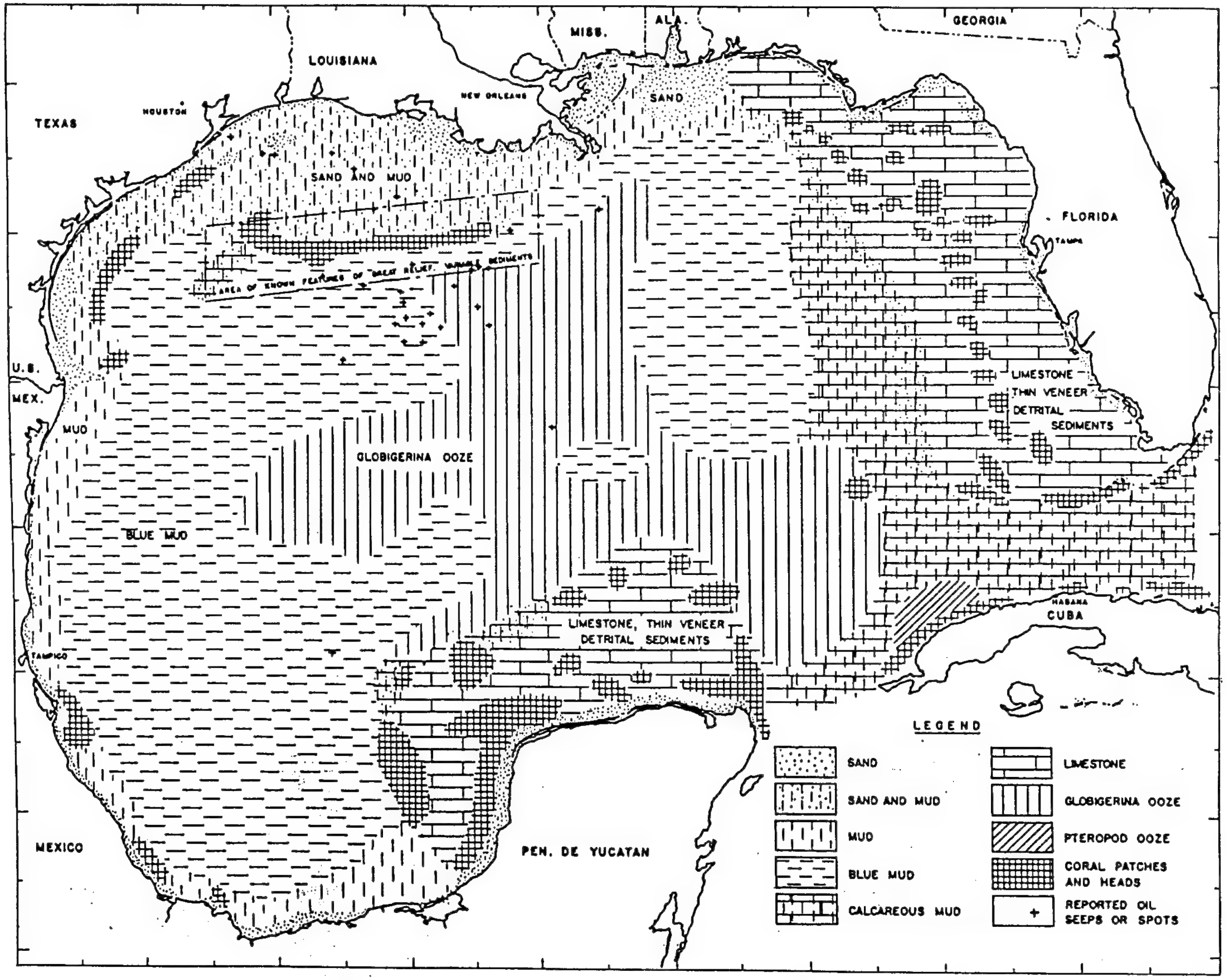

Fig. 2.2.5-3. Distribution of sediment types in the Gulf of Mexico (from Murray, 1961).

2.2.5.4 Sediment Thickness

During its long existence as a basin (late Paleozoic-early Mesozoic) the history of the Gulf of Mexico, like the Atlantic margin, has been one of sediment accumulation and subsidence. Over this period as much as 15,000 m of clastic sediments have accumulated with the thickest sediments presently situated inland beneath the gulf coastal plain (Murray 1961). Thus, sediment thickness is actually thinner beneath the Sigsbee Abyssal Plain. Along the Sigsbee Escarpment sediment thickness is about 9000 m and thins to 2000 m at the foot of Campeche Escarpment. Westward near the Mexican ridge system, the sediments thicken to at least 10,000 m. Figure 2.2.5-4 shows the thickness of the Quaternary sediments (i.e., Recent and Pleistocene) that have accumulated in the deep Gulf of Mexico.

2.2.5.5 Seismicity

The west coast of Mexico and Central America is an active plate margin that is not very far from the Gulf of Mexico (Fig. 2.2.3-4). Thus, one could expect some seismic activity in the western gulf. On the other hand, the western Gulf of Mexico/eastern Mexico is a passive margin and, moreover, the Gulf of Mexico's history is closely linked to that of the western Atlantic. As a result, seismic activity is uncommon to the Gulf of Mexico.

2.3 GEOCHEMISTRY *by Richard A. Jahnke*

The abyssal seafloor may be generally characterized as a cold, low-energy, low-organic input environment. With the exception of regions immediately adjacent to seafloor vent communities, abyssal organisms depend on the slow rain of organic materials from the overlying surface waters to meet their metabolic needs. Most diagenetic reactions occurring in deep-sea sediments are biologically mediated. Sediment geochemical characteristics, therefore, are also controlled by this transfer of organic matter to the deep ocean. Because organic matter produced in the photic zone is very efficiently utilized by organisms living in the upper portion of the oceanic water column, very little (approximately 1–2%) of the organic matter produced in the surface waters reaches the deep ocean. This low rate of input is reflected in low sediment accumulation rates which generally are less than 2 cm per 1000 years.

With little chemical energy, in the form of organic matter, arriving at the abyssal seafloor to fuel diagenetic reactions, the overall redox characteristics of abyssal sediments do not vary greatly with depth in the sediments. In general, these sediments do not become depleted in oxygen within the upper 20–40 cm. In this regard, these sediments are radically different from most near-shore sediments where strongly reducing conditions are commonly observed very near the sediment surface.

Abyssal systems are also quite stable. They are not subjected to the seasonal and diurnal variations that so significantly influence biological and chemical processes at the earth's surface. Thus, significant temporal changes in the geochemical characteristics of abyssal sediments are extremely rare and are restricted to small patches of the seafloor

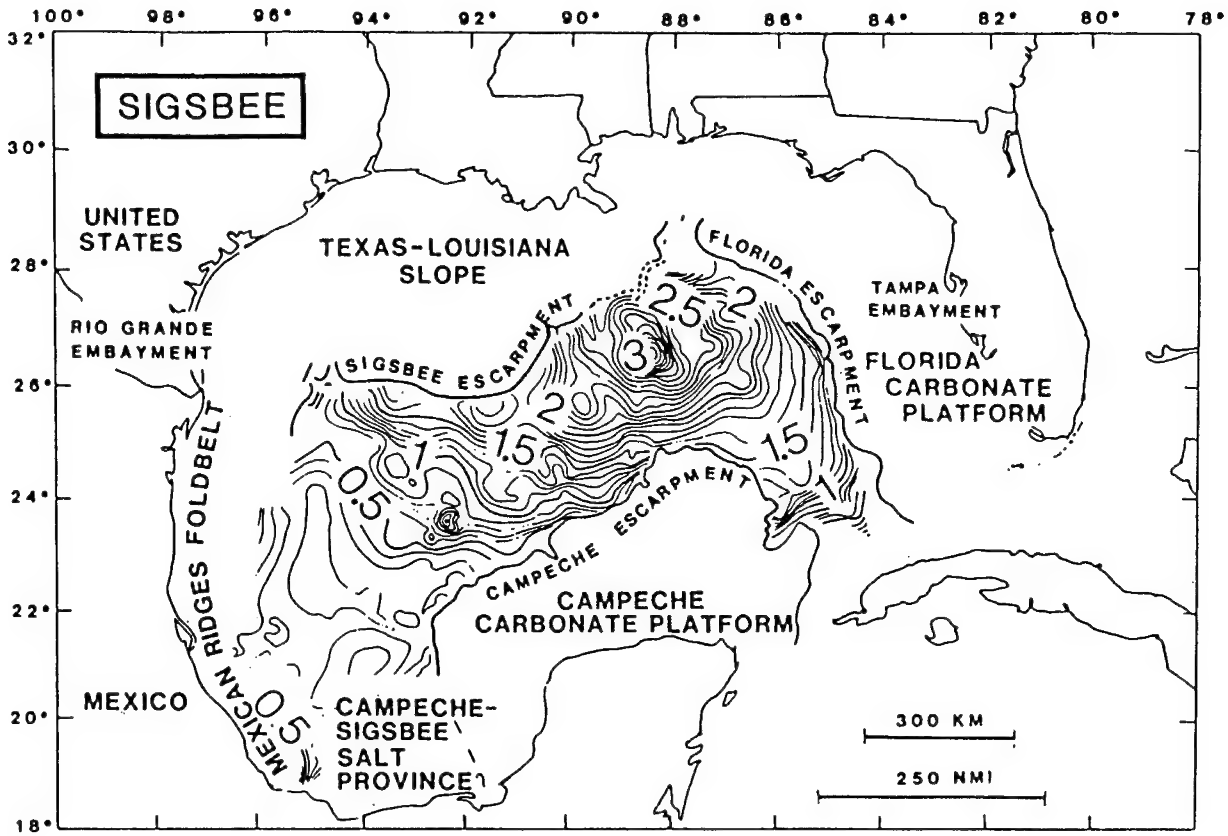

Fig. 2.2.5-4. Sediment thickness map of the Pleistocene sediments for the deep Gulf of Mexico (from Shaub et al., 1984). Contour interval is 0.1 km.

impacted by catastrophic events such as the deposition of a dead whale carcass or sediment debris flow from an adjacent topographic high.

Despite the above characteristics, important regional differences do exist. The bottom water oxygen content of deep Atlantic waters is approximately twice that of the deep Pacific. This is because the majority of deep waters are formed in the North Atlantic and slowly circulate to the North Pacific were they upwell and return to the Atlantic in intermediate and surface layers. During this global transit, oxygen is continually consumed by respiration. By the time the deep waters enter the Pacific, approximately half of the oxygen that was dissolved in the water when it left the North Atlantic has been consumed resulting in this inter-basin difference.

Similarly, carbon dioxide released during respiration tends to acidify the bottom waters making them more caustic to calcium carbonate. Thus, the deep waters in the North Pacific tend to be significantly undersaturated with respect to calcium carbonate while those in the North Atlantic are supersaturated. These differences are reflected in the composition of the bottom sediments. While calcium carbonate is a dominant phase in the Atlantic, it is generally absent from deep North Pacific sediments.

In summary, the abyssal seafloor may be characterized as a slowly accumulating environment, exhibiting relatively slow rates of solute exchange across the sediment-water interface and minor down-core diagenetic changes. It must be recognized, however, that this environment is determined by the slow rain rate of organic matter to the sediment surface and not by an intrinsic inability to react with organic materials. Any increase in the particulate flux of metabolizable organic matter would result in the increase in diagenetic reaction and seafloor solute exchange rates.

2.4 Ecology of the Deep Sea *by Gilbert T. Rowe*

2.4.1 Background

The deep-sea ecosystem has some unique qualities which make it a possible alternative to receive and assimilate wastes which are presently deposited on land or in the coastal zone. To a large degree, these qualities are the result of the geology, geochemistry and physical environment, which are discussed elsewhere in this report. This brief review is taken in large part from several recent monographs (Rowe 1983; Gage and Tyler 1991; Rowe and Pariente 1992).

2.4.2 Deep Abyssal Plains: Biomass Limited by the Input of Organic Detritus

The deep ocean, away from continental margins, has limited input of organic detritus. The primary production (photosynthesis) in surface waters above such environments is low because inorganic nutrients are limiting due to distance from land. In the central gyres of the major basins, such as the Sargasso Sea in the western North Atlantic, these rates are

less than 100 mg C $m^{-2}d^{-1}$ (reviewed in Berger et al. 1989). What little organic matter is produced undergoes considerable transformation within the surface mixed layers of several hundred meters (Karl and Knauer 1984), leaving only a small rain of particulate matter composed of dead cells, carcasses, and fecal pellets to sink or be transported to great depths. On the order of a few percent of surface production is left to nourish life on the seafloor (Honjo et al. 1982). This small influx of potential energy is all that is left, and this is what limits biological processes 3 to 6 km deep on the abyssal seafloor (see Rowe and Pariente (1992) for review).

Although the water is dark and cold at such depths, experiencing little in the way of daily, seasonal or annual variations in temperature, a seasonal variation in the rain of detrital organic matter has been detected in year-long sediment traps at a few localities (Deuser and Ross 1980). On occasion, a pulse of particulate matter from the surface forms a visible layer of flocculent material on the seafloor apparently relatively unaltered by biological processes (Lampitt 1985; Hecker 1990a).

While abyssal plain sediments appear uniform and monotonous, most have been formed by turbidity flows which occurred during periods of lowered sea level. These flows formed deep canyons on the continental slope. Today, the canyons often act as conduits for transporting material from the continental margins into the basin interior (Gardner 1989). On the continental rise, the canyons are characterized by high depositional levees and ultimately fanlike hills, but in the deep, central regions of major basins, the flow deposits have formed monotonous abyssal plains with little topographical relief. Some canyons have a unique fauna of relatively high biomass compared to adjacent slopes (Rowe 1971; Hecker 1990b), but the abyssal plain environments are necessarily monotonous. "Benthic storms" occur in which current velocities are high enough to resuspend sediments (Gardner and Sullivan 1981; Gross et al. 1988; Richardson et al. 1993). Benthic storms are known to occur in fairly well-defined areas typified by deep boundary currents.

2.4.3 Deep-Sea Biomass and Related Processes

The distribution of living biomass in the deep sea is a salient manifestation of this ecosystem. The biomass of the macrofauna, the most well-studied component of the benthic community (Rowe 1983), declines exponentially as a function of depth. Its distribution can be mapped based on published data for each of the separate basins across those areas in which surrogate waste isolation sites have been identified for this study.

The central Gulf of Mexico abyssal plain, the Sigsbee Deep, is located at 3.75-km depth due south of Galveston. The sediments are composed of fine lutite (clay) exported from the continental margin, most likely as turbidity currents flowing down the Mississippi Canyon and Mississippi Cone during sea-level transgressions. The slopes and rises of both the northern and southern Gulf are underlain with salt diapirs. Petroleum deposits are associated with these diapirs, as are "seep" communities which utilize oil- and gas-derived products for potential energy. Biomass on the Sigsbee Deep is low because surface primary production in the central Gulf is low, and because seafloor temperature is relatively high for abyssal depths (3.5°C). While the abyssal plain is close to U.S. ports from which waste materials could be transported (see Section 3.3, **Site Selection Model**), the abyssal plain

lies almost entirely within the Mexican Exclusive Economic Zone. To utilize fully the Gulf of Mexico abyssal plain for the isolation of wastes would require cooperation with Mexico. There are no quantitative estimates of bacteria, meiofauna, or megafauna from the Sigsbee Abyssal Plain, although one sediment oxygen demand measurement has been made in the eastern deep gulf (Smith and Hinga 1983). Considerable meiofauna data are available from the northern continental margin from the shelf out to greater than 2-km depth (Pequegnat et al. 1990).

A similar pattern of biomass of macrofauna is found in the western North Atlantic (Rowe et al. 1982). The rate of decline into the abyss is about the same as that for the Gulf of Mexico (Fig. 2.4.3-2), but the abyssal plain is located at substantially greater depths (5.3 km). As with the Gulf of Mexico, one or two hundred small macrobenthic invertebrates can be expected per square meter of bottom across the two surrogate sites identified for waste isolation. The proximal site, Atlantic-1, on the Hatteras Abyssal Plain, has been studied extensively. Data are available on species composition and zonation from a long list of authors as a result of the samples collected off Woods Hole by Howard Sanders (Sanders et al. 1965) and off North Carolina by R. J. Menzies (Menzies et al. 1973). Quantitative biomass data are available on bacteria (Deming and Baross 1993), meiofauna (Tietjen et al. 1989), macrofauna (Rowe et al. 1982; see figure 2), megafauna (Rowe and Menzies 1969; Haedrich and Rowe 1978), sediment trap fluxes (Honjo et al. 1982 and others), and sediment oxygen demand (Smith and Hinga 1983). At the distal surrogate site, Atlantic-2, on the Nares Abyssal Plain, some data have been collected, but comparatively little has been published. From what information is available, it appears that stocks and rates are lower there, as might be expected.

The Pacific continental margin has a similar pattern for the macrofauna biomass (Fig. 2.4.3-3), but with some distinctive differences. In general, the biomass is higher at any given depth, as the map illustrates. This could be expected, since surface productivity is higher in the upwelling-influenced surface waters of the eastern Pacific and since sediment oxygen demand out and away from the slope is elevated compared to similar depths in the Atlantic (Jahnke and Jackson 1992; Rowe et al. in press). The notable exception to these patterns is in the oxygen minimum zone on the upper continental slope (100- to 1000-m depths). In this zone, oxygen concentrations are reduced to 5% of saturation or less, most of the invertebrate fauna are eliminated, and oxygen demand by the sediments is diminished compared to values at lesser depths where oxygen is not limitingly low. The data available from an offshore surrogate site, Pacific-2, have been used to model the cycling of organic matter as a means to understanding the potential export of contaminants from a deep-ocean site (see Section 5.4.1).

2.4.4 Faunal Zonation

Across any environmental gradient, species of organisms are going to be partitioned in space in relation to and as a function of competition among species. This also occurs in the deep sea across the depth gradient. Populations occur in relatively narrow zones running as parallel lines perpendicular to the bathymetry (LeDanois 1948; Menzies et al. 1973). Such zones occupy vertical depth increments of several hundred to several thousand meters (Carney et al. 1983). The boundaries of the zones can be abrupt and narrow, which has been

observed on their near-shore or shallow margins, or indistinct, which is more often encountered offshore on the deeper boundary of the zone (Rowe and Menzies 1969). It has been suggested that the gradient which causes deep-sea zonation is the declining input of organic matter to the seafloor, rather than temperature, currents, or sediment type (Carney et al. 1983). The exponential decline in biomass across zones reinforces this suggestion.

Waste isolation should be carried out within zones rather than on zonal boundaries, if possible. If zones are caused by competition for diminishing supplies of organic matter, the artificial introduction of organic matter with waste material may alter the competitive advantages of the different species, and thus alter the zonation pattern. It is likely, therefore, that species composition would change at a waste isolation site. Unique or highly altered zones (or patches) of organisms may be created due to the introduction of organic matter and new substrate.

2.4.5 Species Diversity

Based on a relatively few qualitative collections off the northeast U.S. in the early 1960s, it was recognized that numbers of species are relatively high in the deep sea, even though animal abundances and biomass both decline precipitously with depth (Hessler and Sanders 1967). The variation in diversity or species richness follows a parabolic pattern relative to depth, with maximum numbers of species occurring at intermediate depths of 1 to 4 km (Rex 1983). It has been suggested (Sanders 1968) that diversity patterns are a function of geologic and ecologic stability. Quantitative sampling along the base of the continental slope of the NW Atlantic suggests that several hundred different species can be expected per square meter of seafloor, and that the diversity of species is greater than previously thought (Grassle and Maciolek 1992). These authors found that diversity varies more markedly across than along the bathymetry, due in part to the zonation described above, but variations along depth contours (presumably within the "zones" described above) suggests that the deep ocean is more speciose than heretofore suggested. The latter authors have inferred that diversity levels are maintained by biogenic microhabitat heterogeneity, an absence of barriers to dispersal, cropping by predators, and division of variable food resources into relatively small patches in time and space. This "heterogeneity" would be increased by the presence of a waste isolation site.

It can be expected that introduction of alien wastes, especially if it is rich in organic matter, will alter species diversity on the deep seafloor. This could occur in two ways: competition or toxic effects. Where competitive advantage alone causes the species composition to change, the species list length might remain extensive. However, the species list might be quite short if toxicity is a problem. These two alternatives would not be mutually exclusive. A part of the competitive selection process could be an ability to survive being buried.

2.4.6 Reproduction

Rates of reproduction in deep-living species tend to be low compared to shallow-water benthos (see Gage and Tyler 1991). While shallow species tend to produce large numbers

of eggs and larvae which are planktotrophic (feed on plankton in the water column during development), deep-living forms tend to produce fewer eggs and larvae. These develop in brood pouches or have lecithotrophic (contain yolk-like material) planktonic stages. Many species appear to produce gametes in a periodic manner, and it is thought that this may be in response to a seasonality in the input of detrital organic detritus from surface waters, which can be periodic (see above).

If gametogenesis (development of eggs and sperm) is a response to the input of organic matter, as suggested by the occasional periodicity that is observed both in particle fluxes and in gamete formation, then it might be expected that large inputs of organic-rich material in a waste isolation industry could stimulate gametogenesis in the resident fauna. In the numerical simulations of the biota of an abyssal plain benthic ecosystem (see Section 5.4.1), reproductive products are increased in proportion to increases in biomass following dumping. The rate per unit biomass or frequency of gametogenesis in time, however, are not altered in the model because there is too little information on these variables in natural populations.

2.4.7 Recruitment

Recruitment is the rate at which larvae and juveniles resupply an area of seafloor with new individuals. It occurs through the influx of planktonic stages settling into the area or by the maturation of brooded young. The rates at which this occurs naturally in the deep sea can be expected to be slow, based on the minimal amounts of detritus that reach the seafloor and on preliminary in situ experiments with sediment trays, carcasses, enriched sediments, etc. (Grassle and Morse-Porteus 1987).

2.4.8 Large Scavengers

The deep ocean is characterized by a group of organisms which find and consume carcasses of large organisms that had died near the ocean surface. These roaming scavengers were first observed in photographs taken by deep-sea cameras that were anchored to the seafloor above bait, such as an open can of cat food. These are characterized by indigenous fishes (Rowe et al. 1986) and invertebrates (Smith 1985), including a large cosmopolitan species of the crustacean amphipod *Eurythenes grillus* (Ingram and Hessler 1983; Smith and Baldwin 1984). It might be expected that such species will be attracted to waste isolation sites.

2.4.9 Potential for Deep-Ocean Commercial Fisheries

A large variety of relatively robust edible fish species lives at all depths of the open oceans (Haedrich and Merrett 1988). In the east Atlantic, the black scabbard *Aphanopus carbo*, considered a local delicacy in Madeira, is fished commercially to a depth of up to 1600 m. Its range has been reported to 2.2-km depth (Bridger 1978). Squids and octopods live to depths of several thousand meters, and are actively fished (FAO 1983). Unfortunately, their life histories, absolute abundances, and biomasses, are impossible to determine

with present technology. The deep Atlantic abyssal plains are dominated, albeit at relatively low abundances, by the grenadier, or rattail, *Nematonurus armatus* (Macrouridae). A number of important commercial fisheries extend to depths of up to 1 km. These include the orange roughy (family *Hoplostethidae*) and the sablefish (family *Anoplopomatidae*). Off the southeast U.S., the wreckfish, *Polyprion americanus,* is known to occur to depths of 1 km and is found in fishable concentrations on the Blake Plateau at depths of 450 to 600 m (Ulrich and Sedberry, unpublished ms.). Invertebrates are also fished on the continental slope. In the western Atlantic this includes the North American lobster *Homarus americanus* and the red crab *Geryon quinquedens*. A number of large crustaceans exist at relatively great depths, such as the giant isopod (pill bug) *Bathynomus giganteus*, and it is reasonable that fisheries will develop to exploit such populations when they are discovered, if they are profitable.

In conclusion, although commercial fishing is conducted in the deep sea, it is confined principally to the continental slopes to depths of little more than about 1 km. This is important because it means that contaminants on the abyssal seafloor far from shore at depths considerably greater than present fishing efforts will not enter a food chain directly utilized by man. Such fisheries do not exist because there is not enough organic matter reaching the deep sea to support the higher levels of the food chain which man could harvest. That is, the "maximum sustainable yield" (MSY) of a potential fishery is very low compared to shallow-living species. Because this MSY is low, such species are susceptible to overfishing. This occurs frequently before regulatory agencies can set limits on the fishery: stocks are depleted below a level of abundance at which the population can sustain itself. The fishery is lost and the species may not recover. Such a scenario is likely for any newly discovered fishery at great depths. Also, the depths are so great that pulling the gear necessary to catch a relatively depauperate population there is prohibitively difficult and expensive. That is, the "catch per effort" (CPE) is also very low.

There are, however, other theoretical considerations: if commercial fisheries on the abyssal seafloor are limited by inputs of organic matter, and if waste isolation introduces large quantities of relatively reactive organic matter to these environments, it might be hypothesized that the biomass of palatable fish or invertebrate species will be increased, either among those species indigenous to the site in question or by recruiting outlying species into the site as opportunistic pioneer predators or scavengers. From such hypothetical increases in fish or invertebrate biomass, new commercial fisheries might be developed. The development of new fisheries would be a bonus of course, but monitoring would have to include any possible contaminant burdens transferred from the isolated wastes to the food chain. Estimates of such possibilities could be modeled in a fashion similar to that for gamete export in Section 5.4.1.

2.4.10 Vents and Seeps

There are exceptions to the low biomass characteristics of the deep sea. These are the hydrothermal vents at continental plate boundaries at which sulfide in hydrothermal waters nourishes symbiotic bacteria living within large invertebrates, namely vestimentiferan worms, clams, and mussels. These are at plate boundaries, and not in the central basin areas where waste storage sites might be located (see Section 3.3, **Site Selection Model**).

A second exception is along continental margins where hydrocarbon seeps have been discovered. These are common in the western Gulf of Mexico in association with offshore oil and gas deposits. These seep communities can be expected wherever subsurface fossil deposits of organic matter are found. Deep-ocean waste isolation should avoid areas where seep and vent communities are likely to be encountered.

3.0 SITE SELECTION

3.1 Rationale and Procedure for Site Selection Process *by David K. Young*

3.1.1 Background

The only Federal regulation, not considering those issues on the scope of international treaties (provided in Section 1.2, **Environmental Regulations**), that would be applicable to deep-ocean disposal is the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972, Public Law 92-532. MPRSA specifies that all proposed operations involving the transportation and disposal of waste materials into oceanic waters have to be evaluated for determination of the potential environmental impact of such activities. These environmental evaluations have to be in accordance with applicable criteria published in Title 40, Code of Federal Regulations, Parts 220-228 (40 CFR 220-228). At the very minimum, any disposal of waste materials into the deep ocean would have to meet the criteria and factors specified by the MPRSA.

3.1.2 MPRSA Criteria for Site Selection

The MPRSA (Section § 228.5) specifically excludes certain oceanic areas from consideration for disposal of materials, such as those of existing fisheries (finfish and shellfish) and navigational utility (commercial and recreational). The Act states that impacts on water quality within disposal sites "... have to be reduced to normal ambient seawater levels or to undetectable contaminant concentrations or effects before reaching any beach, shoreline, marine sanctuary, or known geographically limited fishery or shellfishery." Further, the MPRSA limits the sizes of ocean-disposal sites "... in order to localize for identification and control of any immediate adverse impacts, and permit the implementation of effective monitoring and surveillance programs to prevent adverse long-range impacts." Finally, the Act states that, "EPA will, wherever feasible, designate ocean-dumping sites beyond the edge of the continental shelf and other such sites that have been historically used."

3.1.3 MPRSA Factors for Site Selection

The MPRSA (Section § 228.6) specifically states that the following factors will be considered in selecting potential disposal sites:

(1) Geographical position, depth of water, bottom topography, and distance from coast;
(2) Location in relation to breeding, spawning, nursery, feeding, or passage areas of living resources in adult or juvenile phases;
(3) Location in relation to beaches and other amenity areas;
(4) Types and quantities of wastes proposed to be disposed of, and proposed methods of release, including methods of packing the waste, if any;
(5) Feasibility of surveillance and monitoring;

(6) Dispersal, horizontal transport, and vertical mixing characteristics of the area, including prevailing current direction and velocity, if any;
(7) Existence and effects of current and previous discharges and dumping in the area (including cumulative effects);
(8) Interference with shipping, fishing, recreation, mineral extraction, desalination, fish and shellfish culture, areas of special scientific importance, and other legitimate uses of the ocean;
(9) The existing water quality and ecology of the site as determined by available data or by trend assessment or baseline surveys;
(10) Potentiality for the development or recruitment of nuisance species in the disposal site;
(11) Existence at or in close proximity to the site of any significant natural or cultural features of historical importance.

The Act states that these factors shall be used "... in support of the site designation promulgation as an environmental assessment of the impact of the use of the site for disposal, and will be used in the preparation of an environmental impact statement for each site where such a statement is required by EPA policy."

The intent and purpose of using the MPRSA criteria and factors for evaluating environmental impact of ocean disposal of wastes is to ensure that there would be:

(1) No unacceptable adverse effects on human health and no significant damage to marine resources;
(2) No unacceptable adverse effect on the marine ecosystem;
(3) No unacceptable adverse persistent or permanent effects due to the dumping of particular volumes or concentrations of these materials; and
(4) No unacceptable adverse effect on the ocean for other uses as a result of direct environmental impact.

3.1.4 Deep-Ocean Industrial Waste Disposal Studies

There have been a few studies of concepts for deep-ocean disposal of industrial wastes and for deep-sea mining that have been discussed, proposed, or conducted (several of which are discussed in Section 1.5, **Past Studies**). It has been suggested (Duedall et al. 1983) that the criteria for selection of sites established by the joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), as applied to near-shore waste disposal, be extended to deep-water waste disposal. These criteria are given as site selection considerations to be used subjectively (Table 3.1-1), but lack the objectivity needed to assess potential impacts of various disposal concepts in the less-well-known deep-oceanic environment.

In consideration of the concept that abyssal plains may be suitable regions to receive and accommodate large volumes of sewage sludge and other large-bulk, low-toxicity wastes, Angel (1994) has developed the following criteria:

1. A maximum permissible reduction in dissolved oxygen levels of bottom water beyond the near field of disposal site should not exceed 10% of baseline levels.

2. The extent of the near field should be kept as small as is practically possible to 0.01% of the total area of the abyssal plain in any basin (e.g., three sites of 100 km^2 each would keep the impact within the limits of 0.01% of the abyssal plain area in the northeastern Atlantic basin, suggested by Angel as a potential disposal site).

3. The extent of the far-field effects should also be strictly limited to 1% of the basin's area (e.g., containment versus dispersion for purposes of monitoring).

3.1.5 Deep-Ocean Containment of Radioactive Wastes

The best examples of studies which have developed strategies for site selection of deep-ocean areas suitable for disposal of wastes are those dealing with long-term containment of radioactive wastes. For example, Bowen and Hollister (1981) presented the following mandatory exclusion criteria which have to be taken into account for deep-ocean containment of radioactive wastes:

(1) areas of complex bottom physiography;
(2) areas of current-swept bare rock and regions known to be swept by strong (erosional) bottom currents;
(3) active plate boundaries;
(4) areas littered with ice-rafted rocks and debris;
(5) regions of high biological activity; and
(6) regions of present use.

Many of these would be prime candidate criteria for ensuring isolation of broad categories of industrial wastes other than just radioactive wastes. Other criteria, of lesser importance, which have been listed by Bowen and Hollister (1981) as "areas to be avoided if possible" are:

(1) regions of natural resource potential;
(2) regions of prior dumping activity;
(3) sediments with low ion-exchange properties;
(4) sediments with high organic activity;
(5) areas with little prior database; and
(6) areas with poor to nonexistent navigational aids.

Along similar lines of reasoning, Heath et al. (1983) have considered reasons for certain abyssal plain locations as being suitable (and unsuitable) for containment of radioactive wastes. They state that waste disposal sites should be far from seismically and tectonically active lithospheric plate boundaries and far from active or young volcanoes. Further, suitable sites should contain thick layers of very uniform fine-grained clay and be devoid of natural resources likely to be exploited in the foreseeable future. As a general rule, Heath et al. (1983) state that geological and oceanographic processes governing sediment deposition

Table 3.1-1. Environmental Characteristics to be Considered on Oceanic Dumpsite Selection (from Duedall et al. 1983)

Physical	Sedimentology	Biological
Oceanic flow	Physical and chemical properties of wastes and sediments	Fishing grounds
Circulation	Sorptive capacity	Aquaculture sites
Surface waves	Distribution coefficient	Breeding and nursery grounds
Wind-driven surface currents	Sedimentation	Migration routes
Turbulent diffusion	Sediment dispersion	Productivity
Shear diffusion	Bioturbation	
Vertical mixing	Sediment stability	
Modeling advection and diffusion		

should be well understood and have remained unchanged during past oceanic and climatic changes. Finally, to ensure containment of extremely long-lived radioisotopes, future stability should be predicted by sedimentary records of tens of millions of years of slow, uninterrupted deposition of fine-grained clay.

In another study (U. S. Subseabed Disposal Program), Laine et al. (1983) have addressed the concept of disposal and containment of high-level radioactive wastes within the deep seafloor. Two primary criteria guided the Laine study, that is, the stability and barrier criteria of the site. Of these, the "barrier" criterion would be applicable only to those wastes implanted into deep-sea sediments as a long-term repository, a necessary consideration for containment of long-lived radionuclides. This study is one of the best examples of a systematic site selection process addressing the concept of disposal and containment of wastes in the deep-ocean environment. Laine et al. (1983) reduced large regions of the abyssal seafloor by **phases**, which systematically focused on smaller and smaller areas using **Site Selection Criteria** as defined in Table 3.1-2. The phases described by Laine et al. (1983), as provided in Figure 3.1-1, are defined generally as follows:

Phase 1 – Ocean-Basin Screening Studies: to develop and implement Site Selection Criteria permitting the large scale of ocean basins (100s of square degrees) to be downsized and allowing detailed searches for potentially acceptable regions;

Phase 2 – Regional Studies: using Site Selection Criteria, to reduce relatively large abyssal plain regions to areas (10s of square degrees), and then to reduce areas to sites (1 square degrees) suitable for more detailed study;

Phase 3 – Site Studies: to study in increasing detail, including numerical model sensitivities, the sites identified in Phase 2 (in this phase, identification of the technologies and methodologies needed for the Site Survey Task becomes operative);

Phase 4 – Monitoring Plan: to determine the specific variables to be monitored and how to monitor them; to identify the spatial/temporal scales required for the monitoring schedule (the choice of variables and the schedule of monitoring could, thereby, be guided by numerical model sensitivity studies).

3.1.6 Conclusions

These and other studies, which investigated potential environmental impacts of waste disposal in the deep ocean and identified criteria necessary to minimize detrimental effects, have contributed in various ways in developing our site selection rationale and procedure. This present study differs from most of the previous studies that have been focused on specific, often narrowly defined, waste categories and single oceanic basins or abyssal plains. In addition, engineering concepts for waste delivery systems were often unspecified and economic considerations were separate issues, if they were considered at all. An exception to this generalization is the study of the Woods Hole Oceanographic Institution (WHOI 1991) "An Abyssal Ocean Option for Waste Management." The WHOI study was useful to our guiding philosophy in developing a site selection process that was flexible in addressing different engineering concepts, economic considerations, and environmental scenarios. Charles Hollister (WHOI 1991) addressed the need for flexibility in the site

Table 3.1-2. Site Selection Criteria used to develop and implement a methodology for identifying and studying sites on abyssal plains which may be candidates for use as repositories for industrial wastes (adapted from Laine et al. 1983).

<u>Criterion</u>: Essential or desirable environmental characteristic, e. g., sediments must have a high ionic sorptive capacity

<u>Factor</u>*: Properties that must be considered in order to determine whether a criterion has been met, e. g., permeability or distribution coefficient, Kd

<u>Specification</u>:*: Numerical limits of factors that are required to meet a particular criterion, e. g., permeability must not exceed XX and Kd must be at least YY

*Note: Interactions among factors must be considered and trade-offs identified. Specifications are site-specific.

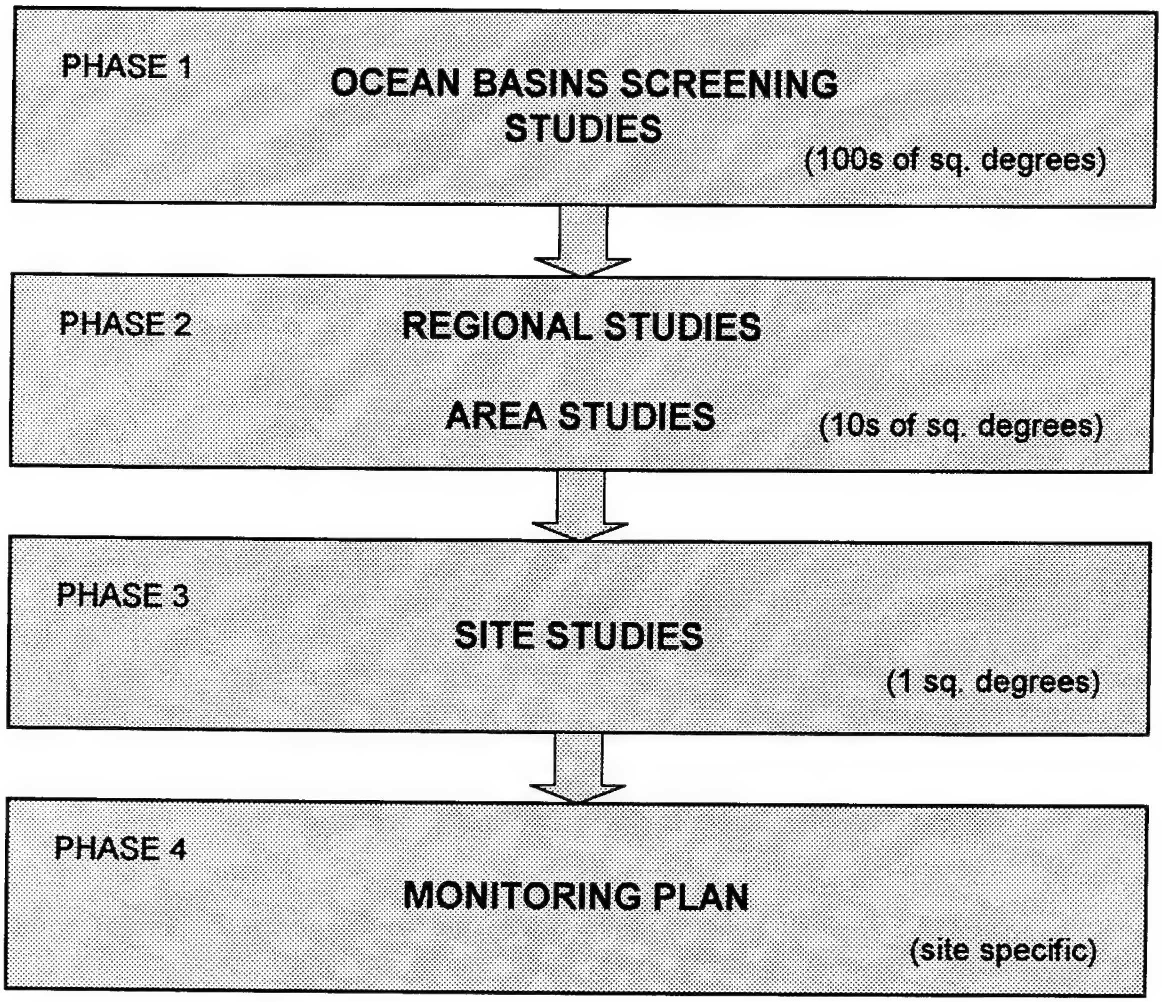

Figure 3.1-1. Site selection process (adapted from Laine et al. 1983).

selection process by suggesting a "geographic filter" overlay system used to screen out areas that have been rejected for various reasons. We have developed a computer-based approach to gain the degree of flexibility provided by Hollister's geographic filter approach but with greatly increased speed and efficiency. We agree with Hollister (WHOI 1991, p.107) that "...the [site] selection process must follow a credible, reproducible, visible approach that integrates technical and social requirements and constraints."

Our site selection procedure was developed on an incremental basis with one step following the next. The first step in this iterative process was to identify selection criteria and factors. The next step was to assemble all literature and relevant data related to the identified criteria and factors into a database. The database, which served as a resource for every aspect of the site selection procedure, was used as inputs to the base maps of the three ocean basins (see Section 3.2, **Mapping**). The final step in bringing all this information into focus was the development of the **Site Selection Model** (see Section 3.3).

3.2 MAPPING *by Frederick A. Bowles and Peter Fleischer*

3.2.1 APPROACH

The process of selecting sites begins with the study and evaluation of large oceanic areas for suitable regions within which sites could be located. Laine et al. (1983) describe this process as ocean-basin screening. It is the first phase of their four-phased approach for downsizing large areas of the seafloor in terms of desirable characteristics or criteria (Table 3.2-1), with each phase focusing on a smaller area of seafloor (i.e., a square-within-a-square) for more concentrated study. In following this approach, we have also adopted the suggestion by Hollister (1991) that this exploratory screening phase be done in a large-scale map format.

For this study, three exclusion factors (Table 3.2-2) were defined in the initial project document that amounted to a *de facto* downsizing of the ocean basins. Otherwise, the screening process is based entirely upon the acquisition and analysis of existing data. The initial step of the process is selecting a detailed bathymetric map and, if necessary, enlarging it to a suitable working scale (e.g., one inch per degree of longitude). This map, in effect, becomes the master reference or base map onto which all other maps, depicting various environmental attributes, are superimposed. Thus a series of maps is developed that can be overlaid, one upon the other, for evaluation of site suitability. The attributes that were mapped were chosen on the basis of: (1) their relevance to the site selection criteria listed in Table 3.2-1, and (2) because of time constraints, our ability to acquire the data quickly.

The above approach is not unlike Hollister's (1991) geographic-filter approach that shades-in undesirable areas while leaving desirable areas unshaded on each map. Theoretically, when all the overlays are superimposed on a light table, any light shining through would indicate areas that should be considered for further study. We have, instead, elected to simply show the distribution of each attribute. Direct mapping of the attributes has the advantage of geographically locating point and line attributes. Mapping also precisely reproduces boundaries

Table 3.2-1. Site Selection Criteria

The following criteria represent environmental characteristics that are essential or desirable for deep-sea waste disposal under a rationale of isolation and containment. Preferably, disposal sites should be located:
1. Away from regions of rugged topography and steep slopes. 2. Away from tectonically and volcanically active areas. 3. Away from regions of intense mesoscale eddy activity, i.e., regions of high eddy kinetic energy in the water column. 4. Away from high-energy bottom environments, i.e., bottom current shear stress should not exceed critical erosional shear stress. 5. Away from undersea cable routes. 6. Away from areas of potential seabed resources, e.g., ferromanganese nodule fields. 7. Away from major shipping lanes. 8. Away from unique environments, e.g., hydrothermal vents, unusual benthic cmmunities, deep-sea trenches, etc. 9. Away from regions of high biological productivity. 10. Away form regions having prolonged, severe weather and (therefore) wave conditions.

Table 3.2-2. Project Definition Exclusions

The following areas, as defined in the initial project proposal, are excluded from consideration for waste disposal:
1. Areas of the sea floor with depths of 3000 m or less. 2. Areas within the Exclusive Economic Zones of foreign nations. The above exclusions are intended to avoid regions of high biological productivity and regions of resource exploration/exploitation and recreation. 3. Areas further than 1800 km (1000 statute miles) from the major waste loading ports.

of areal attributes compiled from other studies. Transforming point and line attributes into areal density distributions makes them suitable for the geographic filter approach, but the requisite interpolations and gridding cause the identities and precise locations of the attributes to be lost. Map plotting and geographic filtering are both valid approaches and are complementary. The maps presented in this section reflect the first approach. In Section 3.3, **Site Selection Model**, the geographic filter approach is developed into a site selection model that utilizes most of the mapped attributes as well as additional attributes.

3.2.2 Ocean-Basin Maps

The project definition exclusions from Table 3.2-2 and the site selection criteria from Table 3.2-1 were applied to those areas of the western North Atlantic, Gulf of Mexico, and eastern North Pacific identified in Figure 3.2-1 to begin the process of selecting the surrogate sites for the technical assessment (see Section 1.4.1, **Engineering Concepts**) and to provide the background for the selection of input parameters for the Site Selection Model, Section 3.3. Figure 3.2-1 illustrates the great differences in size, before exclusions are applied, among the three areas. The difference in size among the areas must be factored into the evaluation when comparing the mapping products. Table 3.2-3 lists the attributes to be mapped for each oceanic area and includes a "Data Sources" section to identify the sources of the information used in compiling the maps.

Figures 3.2-2 through 3.2-7 present the compilation of exclusionary and site selection/optimization criteria for the western North Atlantic. Figure 3.2-2 shows, if one is considering only the bathymetry exclusion, a very large area in the ocean basins and on the continental rise satisfies that criterion. The area north of 37°N is seen to be well traversed by communication cables rendering that area less desirable for waste isolation site locations. The 200-nmi (370-km) Bermuda EEZ excludes a significant basin area from consideration. Figure 3.2-3 shows heavy ship traffic north of 35°N, mixed traffic densities from that latitude down to 28°N, and less than one ship per 1° square southward. Figure 3.2-4 suggests that operating time, in terms of minimizing wave heights, can be maximized using sites between Bermuda and Haiti. Figure 3.2-5 indicates high near-seafloor currents north of 35°N and southward following the continental rise and slope, a manifestation of the Western Boundary Current and cold core rings generated by the Gulf Stream. Areas of low-bottom current intensity are in the central Hatteras Abyssal Plain and at the northern edge of the Nares Abyssal Plain and somewhat to the north. Figure 3.2-6 shows a ferromanganese nodule field to occupy a band on the distant Hatteras Abyssal Plain trending southward from Bermuda toward Puerto Rico; this nodule field must also be excluded. Figure 3.2-7 shows pelagic clay sediments to floor the central Hatteras and Nares Abyssal Plains making these areas desirable for waste isolation sites because of the clay mineral capacity for adsorbing most contaminants in the waste materials. A collection of factors then direct waste isolation site selection to the Hatteras Abyssal Plain south of 32°N (pelagic clay sediment limit) and possibly into the Nares Abyssal Plain.

Figures 3.2-8 through 3.2-13 present the compilation of exclusionary and site selection/optimization criteria for the eastern North Pacific (note that the scale of the Pacific figures is about one-half that of the Atlantic figures). Figure 3.2-8 shows the much narrower width

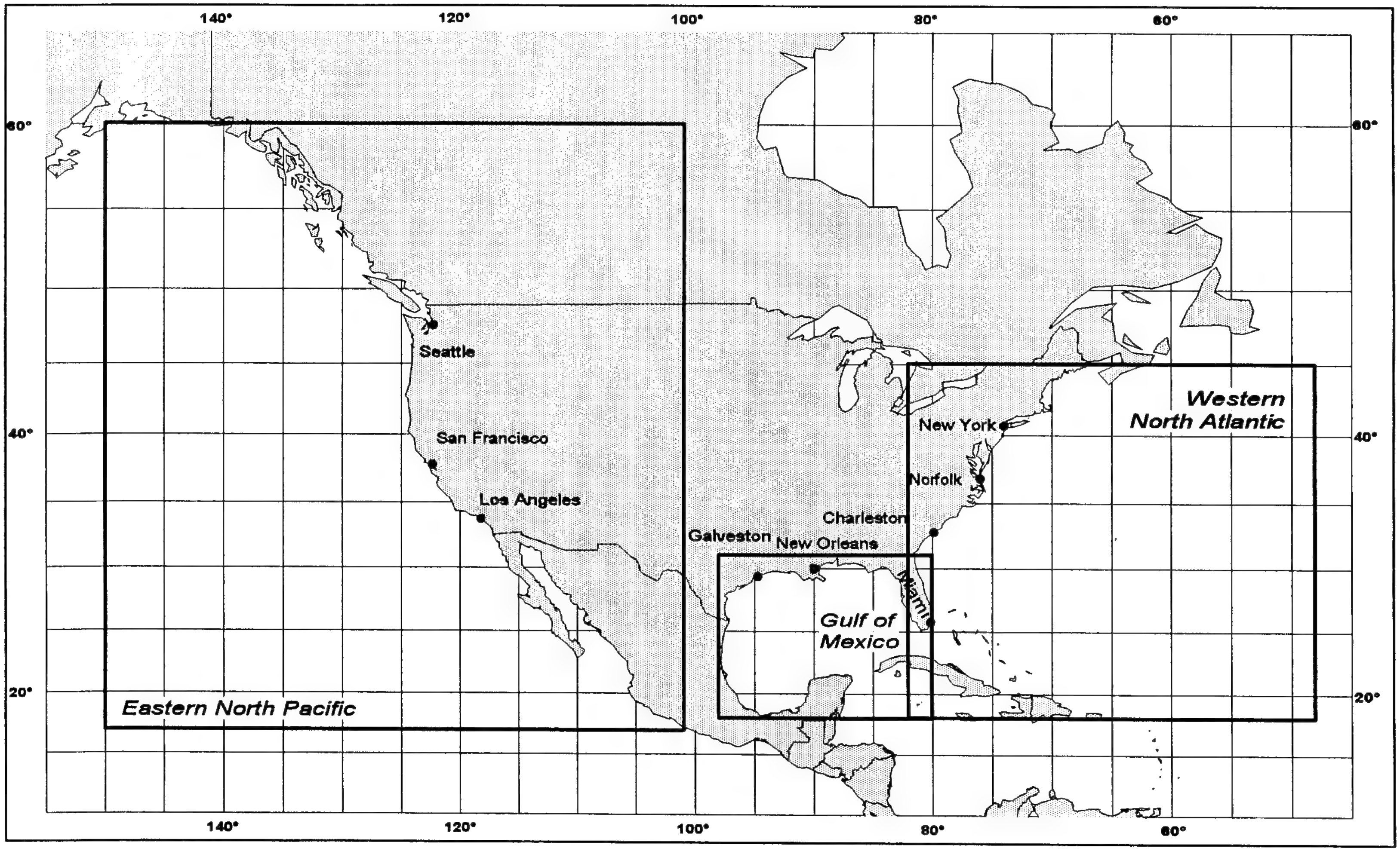

Figure 3.2-1. Areas of map overlays.

Table 3.2-3. Site Selection Maps and Sources of Data

Western North Atlantic (*Site Selection Map..Data Sources*) Shorelines.....1 3000 m contour.....1 Bathymetry.....1 1800 km (1000 nmi) range from coast .....0, 1 Exclusive Economic Zones.....0,2,48 Communications cables.....6, 49 Ship density.....12 Wave heights.....40 Cyclones.....41 Storm Tracks.....41 Bottom current intensity (estimate).....0, 19-29, 52, 53, 54 Polymetallic nodules and crusts.....18 Sediment provinces.....13, 14, 15, 16, 18
Eastern North Pacific (*Site Selection Map....Data Sources*) Shorelines.....1 3000 m contour.....1 Bathymetry.....1 1800 km (1000 nmi) range from coast.....0, 1 Exclusive Economic Zones.....0, 2, 48 Communications cables.....6, 49 ,50 Earthquakes.....9 Ship density.....12 Wave heights.....39 Cyclones.....41 Storm tracks.....41 Bottom current intensity.....0, 30-38, 43, 44, 45, 51, 54 Polymetallic nodules and crusts.....10 Sediment provinces.....10, 11

Table 3.2-3, continued. Site Selection Maps and Sources of Data

Gulf of Mexico
(*Site Selection Map.....Data Sources*)
Shorelines.....1
3000 m contour.....1
Bathymetry.....1
1800 km (1000 nmi) range from coast.....0, 1
Exclusive Economic Zones.....0, 2, 48
Communications tables.....3
Ship density.....12
Wave heights.....40
Cyclones.....41
Storm tracks.....41
Bottom current intensity (estimate).....0, 46, 47, 53, 54
Sediment provinces.....3
Earthquakes.....3
Hydrocarbon seep areas....,.3
Salt structures.....3, 5
Mississippi Fan slump deposits.....5
Mississippi Fan debris flows, channels, and eroded seafloor.....4
Abyssal plain turbidites.....8
Deep-sea channels.....4
Escarpments (Florida, Campeche, Sigsbee).....1, 3, 5, 7
Coral reefs.....3
Brine pool (Orca Basin).....1, 3, 4

Table 3.2-3, continued. Site Selection Maps and Sources of Data

Data Sources

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Table 3.2-3, continued. Site Selection Maps and Sources of Data

Data Sources

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Table 3.2-3, continued. Site Selection Maps and Sources of Data

Data Sources

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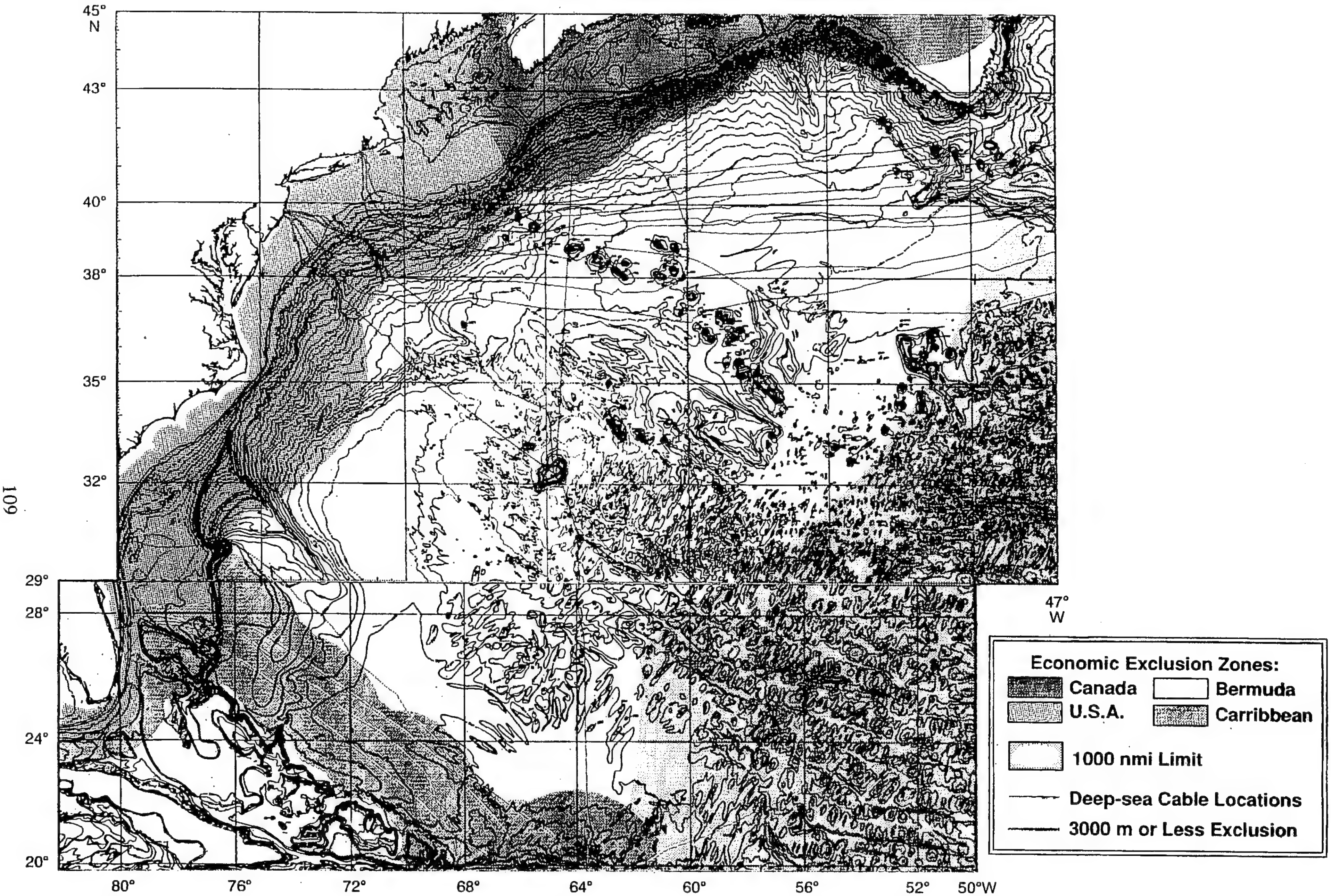


Figure 3.2-2. Western North Atlantic with excluded areas shown, i.e., water depth <3000 m, foreign EEZs, and transport distance >1800 km. Also shown, and to be avoided, are seafloor cable locations.

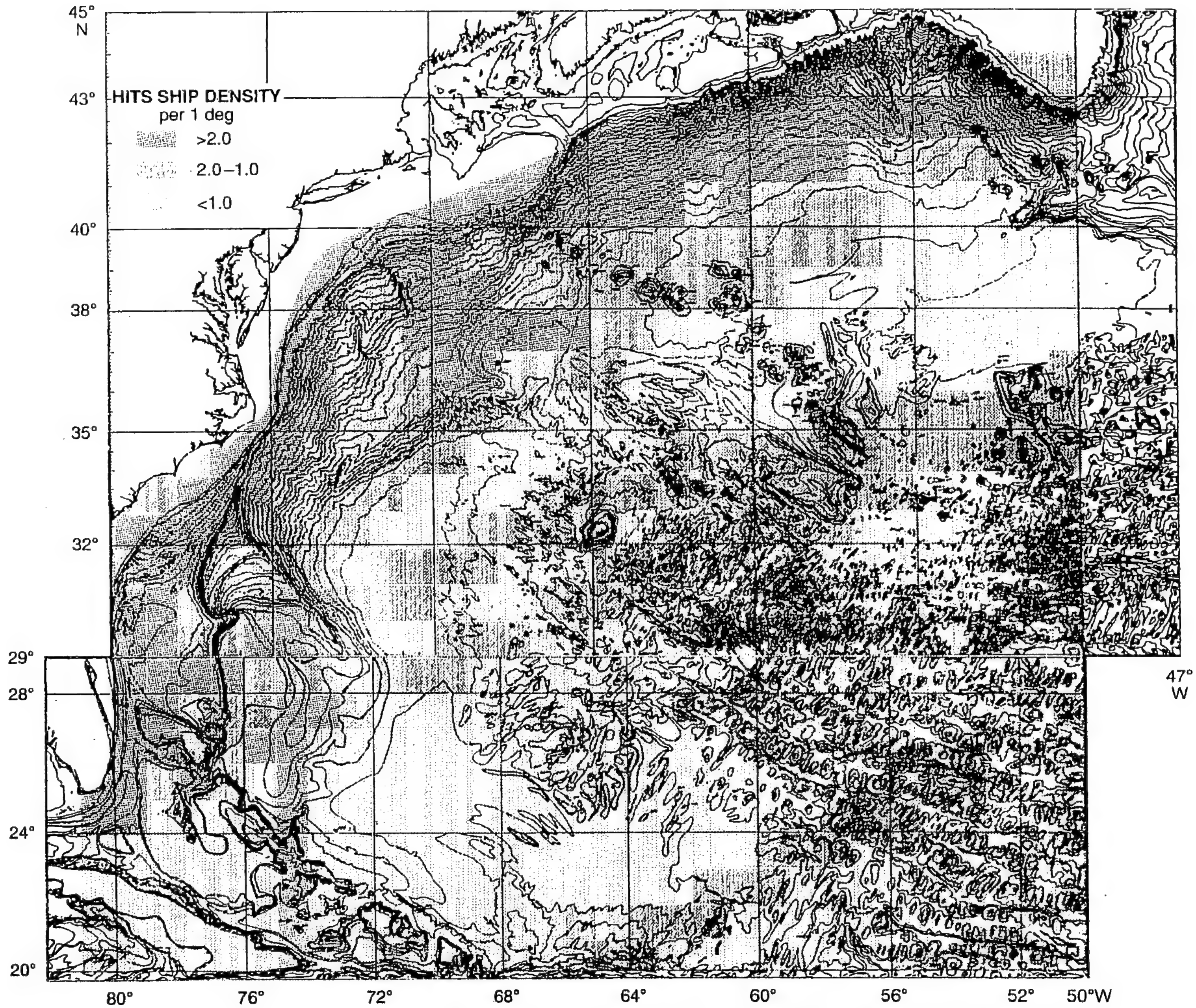


Figure 3.2-3. Western North Atlantic showing areas to be avoided to minimize interference with ship traffic: data are numbers of ships per 1° x 1° area, from Navy Standard Historical Temporal Shipping (HITS) Database.

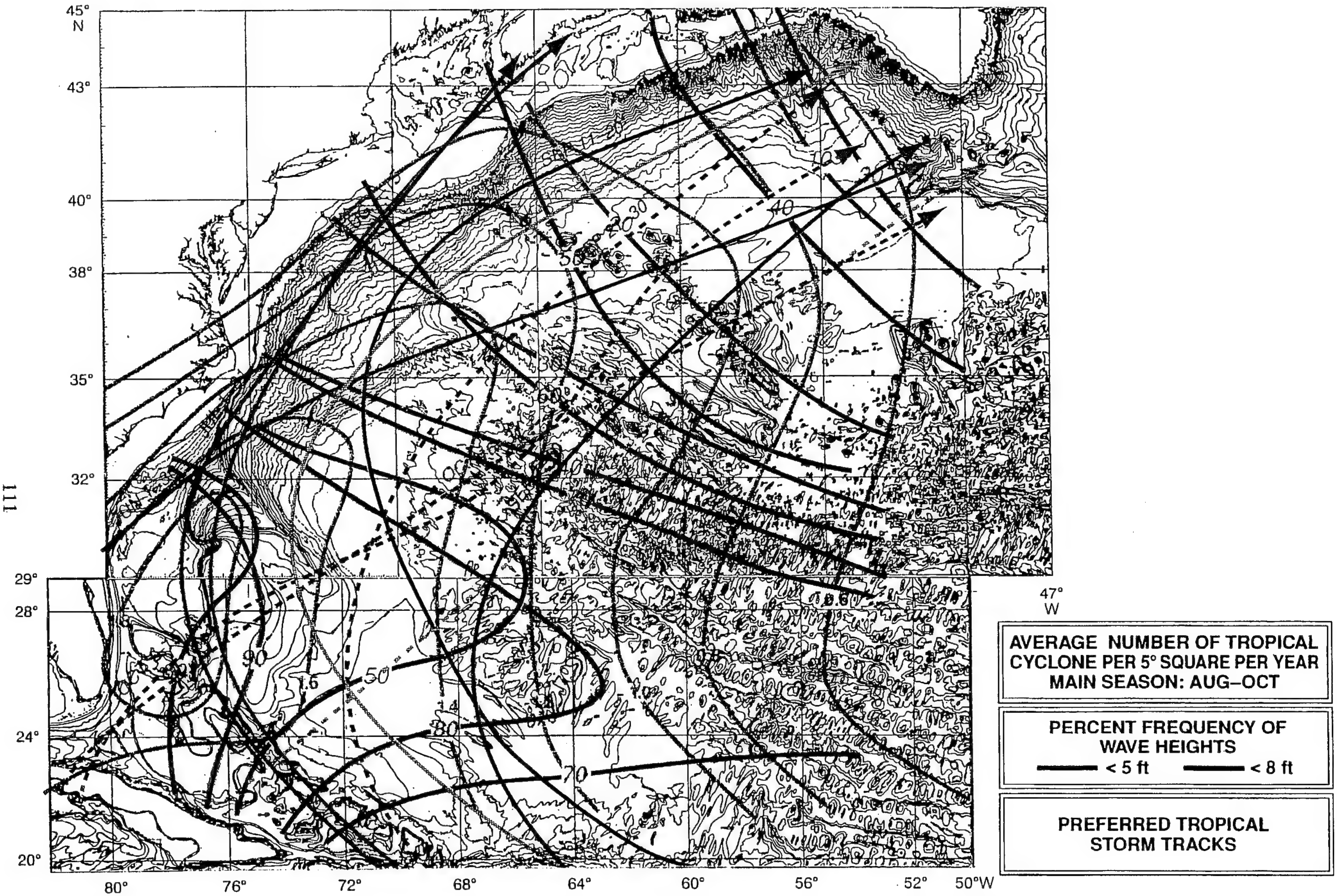


Figure 3.2-4. Western North Atlantic showing areas to be avoided to maximize the number of operating days for an emplacement system: frequency of occurrence of tropical cyclones, preferred storm tracks, and frequency of occurrence of wave heights given.

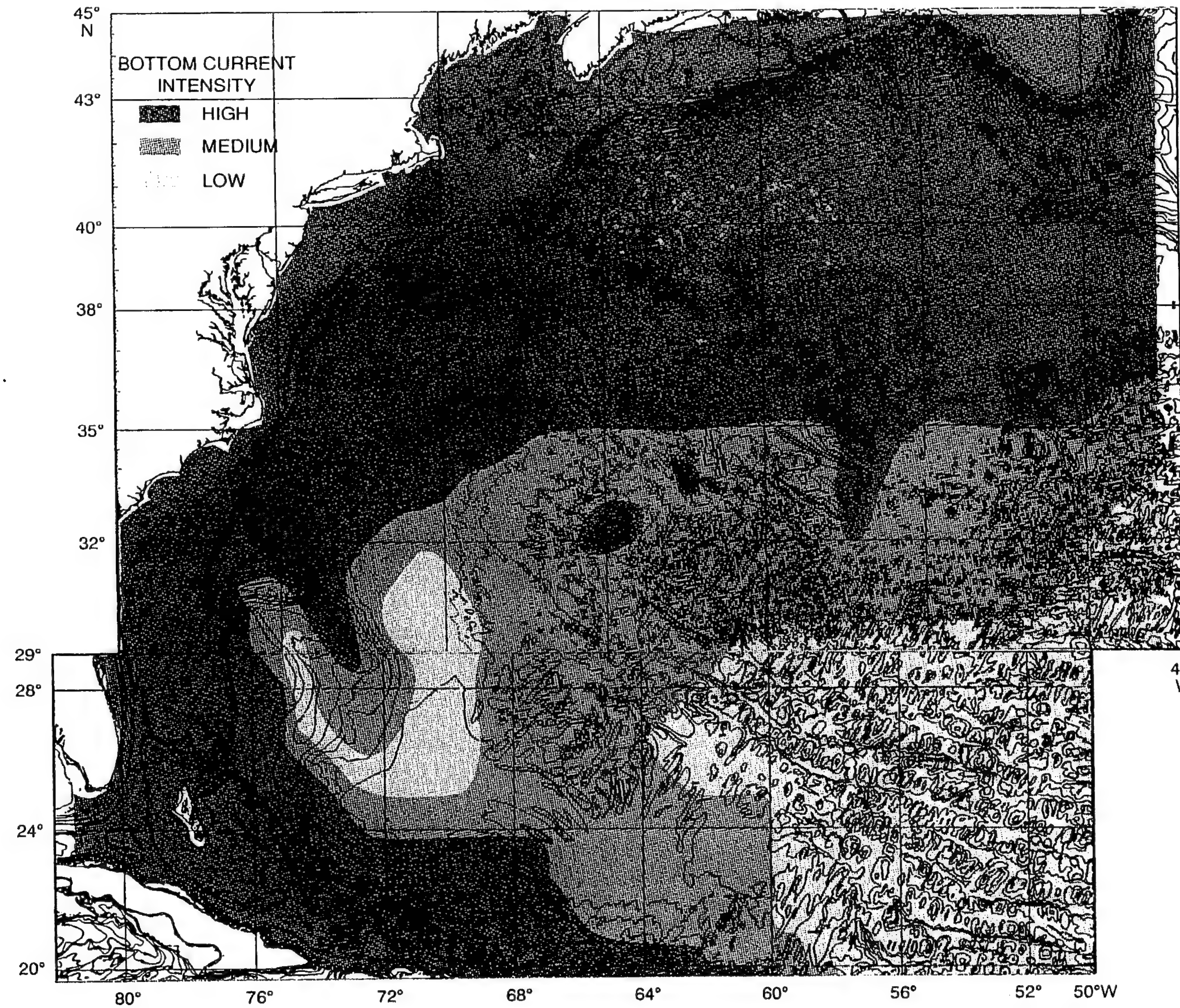


Figure 3.2-5. Western North Atlantic showing qualitative description of near-seafloor current speed.

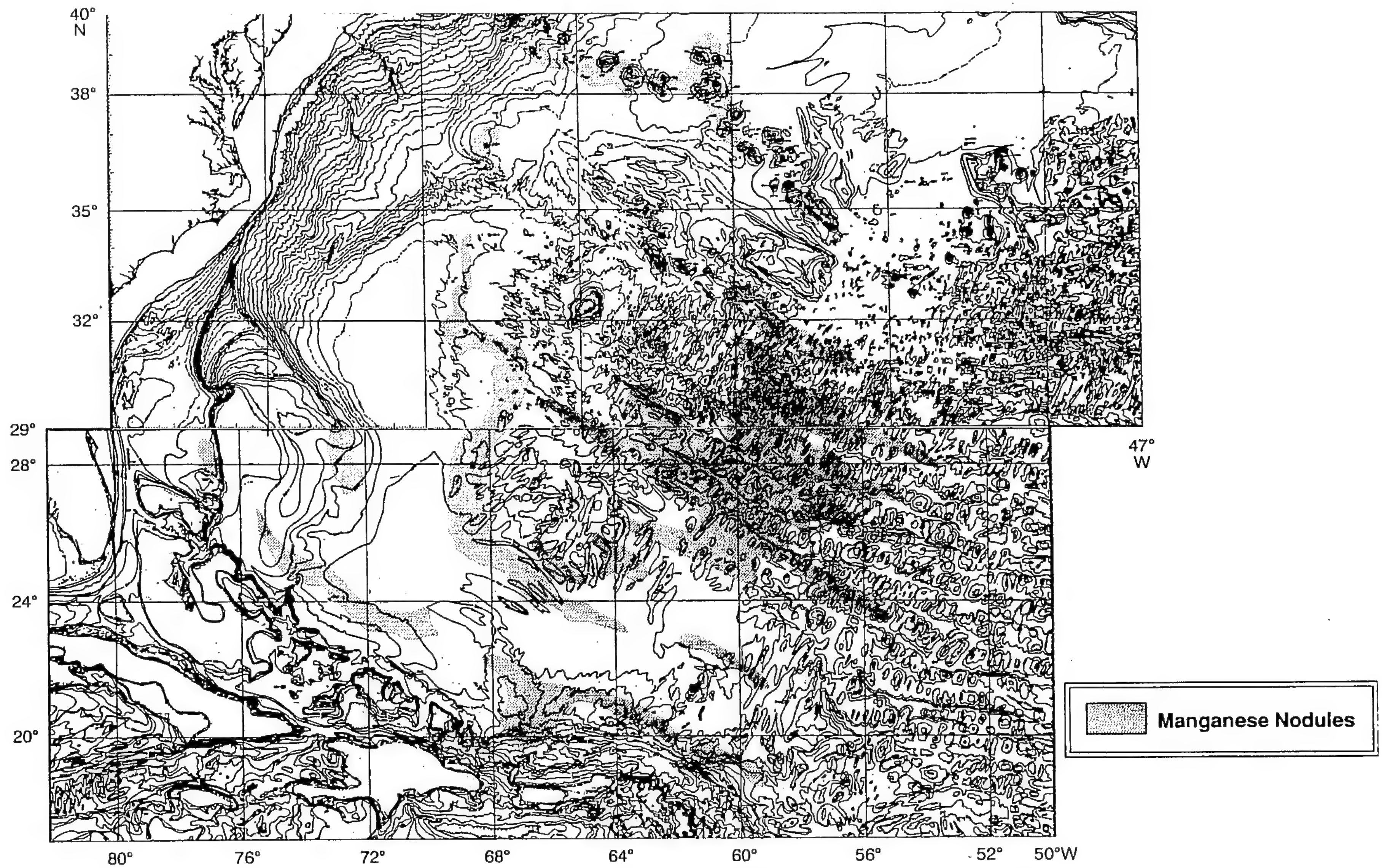


Figure 3.2-6. Western North Atlantic showing distribution of potential seafloor resources (i.e., ferromanganese nodule fields).

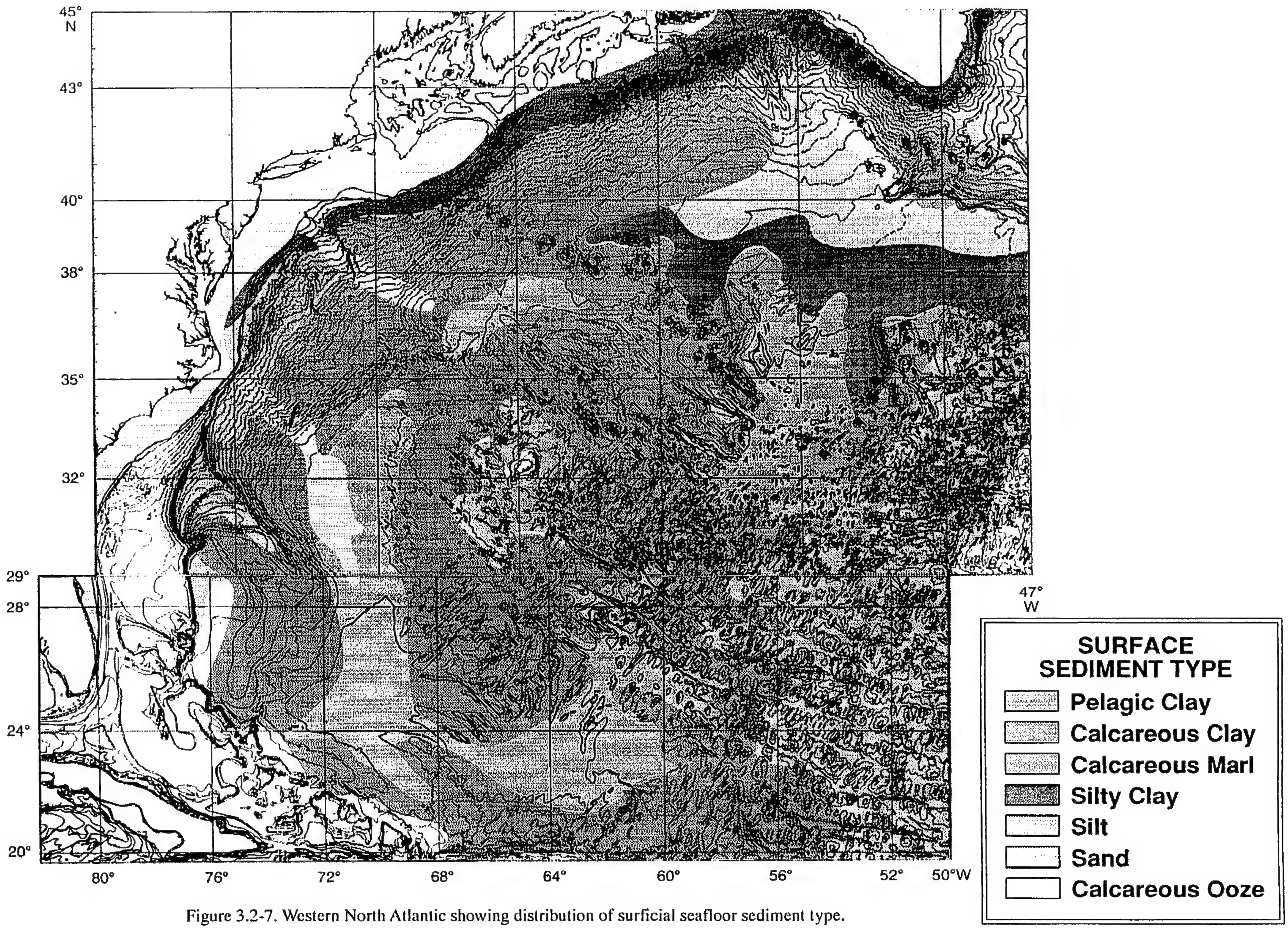


Figure 3.2-7. Western North Atlantic showing distribution of surficial seafloor sediment type.

of the continental shelf and rise on the west coast of the U.S., and correspondingly, much shorter transit distance from west coast ports to reach water depths greater than 3000 m. The bathymetry of this figure also shows the area south of 45°N to be abyssal hills province rather than abyssal plain. Figure 3.2-9 shows ship density to be light south of 47°N and away from the coastal shipping lanes. Figure 3.2-10 shows the wave conditions to improve south of about 32°N and east of 145°W, and south of about 25°N, one gets into the potential paths of tropical cyclones, thus reducing the operating window available. Figure 3.2-11 shows the area 200–300 km from the coast to be subject to relatively low bottom current intensity; this projection is undoubtedly oversimplified and generalized in that one can expect higher currents on topographic highs. Figure 3.2-12 shows significant ferromanganese nodule fields south of 44°N with potential to site waste isolation sites between the fields and/or where the fields are absent closer to the continent. Beyond 300–400 km from the coast and south of 44°N, the sediment type is seen to be pelagic clay in Figure 3.2-13, a desirable environment for waste isolation.

The compilation of exclusionary and site selection/optimization criteria for the Gulf of Mexico are presented in Figures 3.2-14 through 3.2-21 (note that the scale of the Gulf of Mexico figures is twice that of the Atlantic figure set and nearly four times that of the Pacific figure set). Figure 3.2-14 shows that only two relatively small areas, one in the eastern and one in the western gulf, are deeper than 3000 m and outside the EEZs of Mexico and Cuba. Figure 3.2-15 shows the western gulf deep-water area to have lesser ship traffic than the eastern (but twice as densely trafficked as potential Atlantic and Pacific sites). Probably no clear decision regarding site selection can be drawn from the storm, tropical cyclone, and wave height frequency data of Figures 3.2-16 and -17: the potential deep-water areas all appear about equal in desirability or lack thereof. The bottom current intensity projection of Figure 3.2-18 shows no areas of “low” intensity and the “medium” intensity area is totally within the EEZ of Mexico (see Fig. 3.2-14). Figure 3.2-19 shows the entire area of interest to be floored by clay and/or silt-type sediments; the clays should provide adequate adsorptive potential for contaminants reaching the seafloor. Figure 3.2-20 shows the gulf to abound with known and potential unique environments to be avoided by the waste isolation option, most on the mid- to lower continental slopes. Further, the western gulf abyssal plain includes salt features to be avoided. Figure 3.2-21 suggests the western gulf to be more desirable than the eastern because the debris flows and eroded seafloor are not seen in the western area.

3.2.3 Surrogate Sites

The map overlays developed (represented herein by Figures 3.2-2 through 3.2-21) were used to select qualitatively a set of “straw man,” or surrogate, sites for use in this SERDP project. These Surrogate Sites were selected at an early stage in the project, and before the more comprehensive site selection procedures of Section 3.3 were available for implementation, because certain project tasks, such as the engineering assessment, required known geographic locations for analysis to proceed. The preferred method of waste isolation site selection is that to be presented in Section 3.3, where one has the means to quantitatively rank the relative importance of various site attributes and to quantitatively combine these attribute rankings in the site selection process.

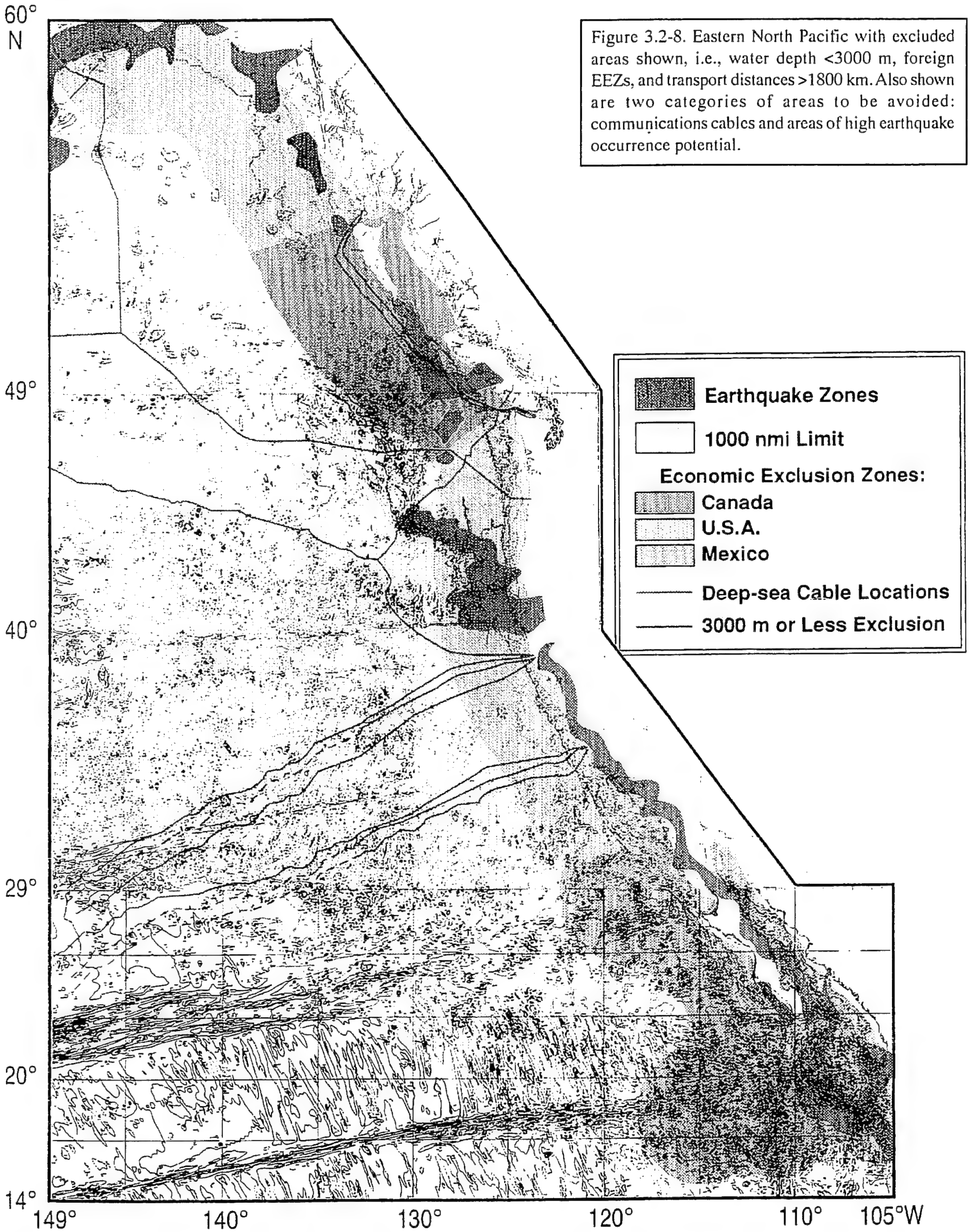


Figure 3.2-8. Eastern North Pacific with excluded areas shown, i.e., water depth <3000 m, foreign EEZs, and transport distances >1800 km. Also shown are two categories of areas to be avoided: communications cables and areas of high earthquake occurrence potential.

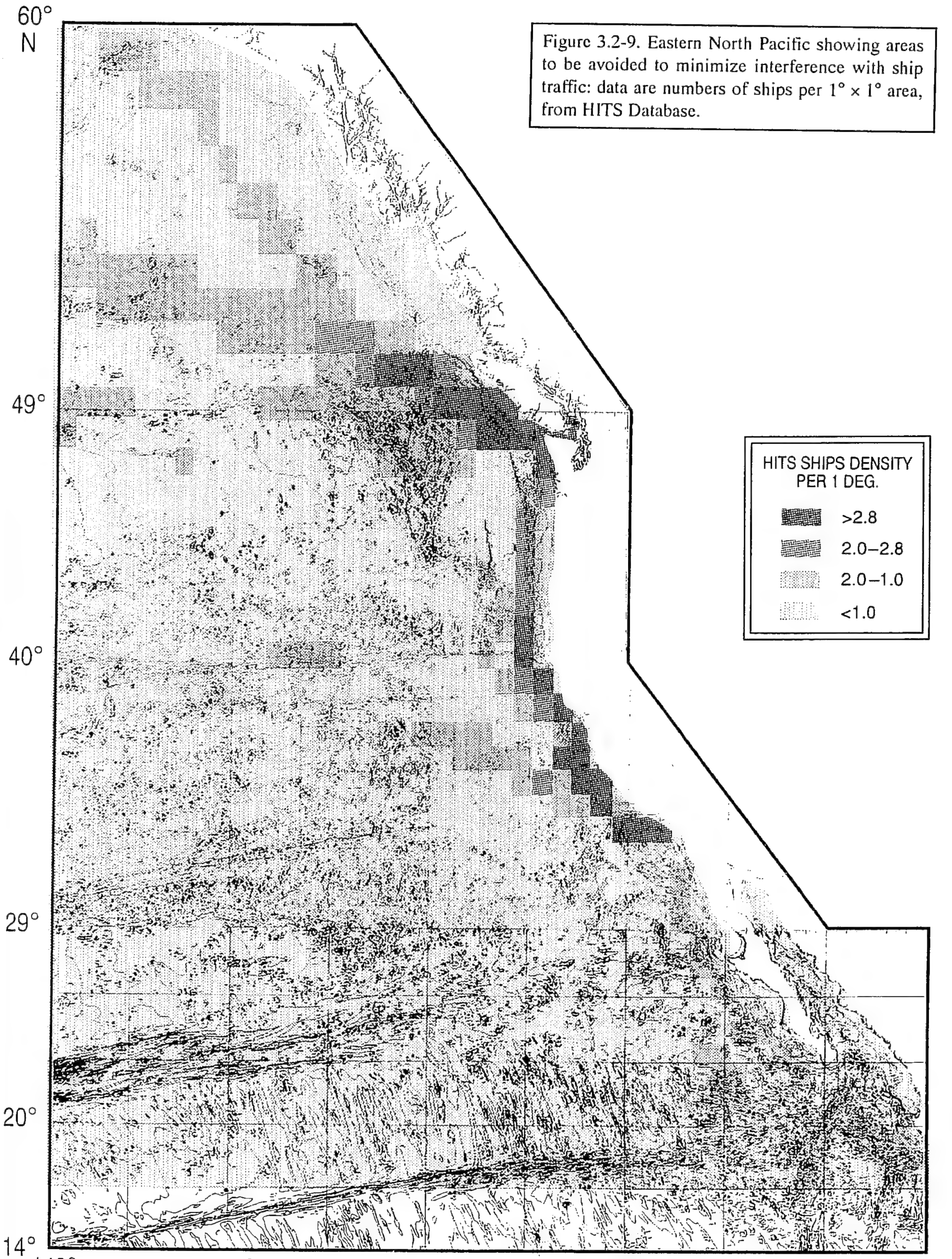


Figure 3.2-9. Eastern North Pacific showing areas to be avoided to minimize interference with ship traffic: data are numbers of ships per 1° × 1° area, from HITS Database.

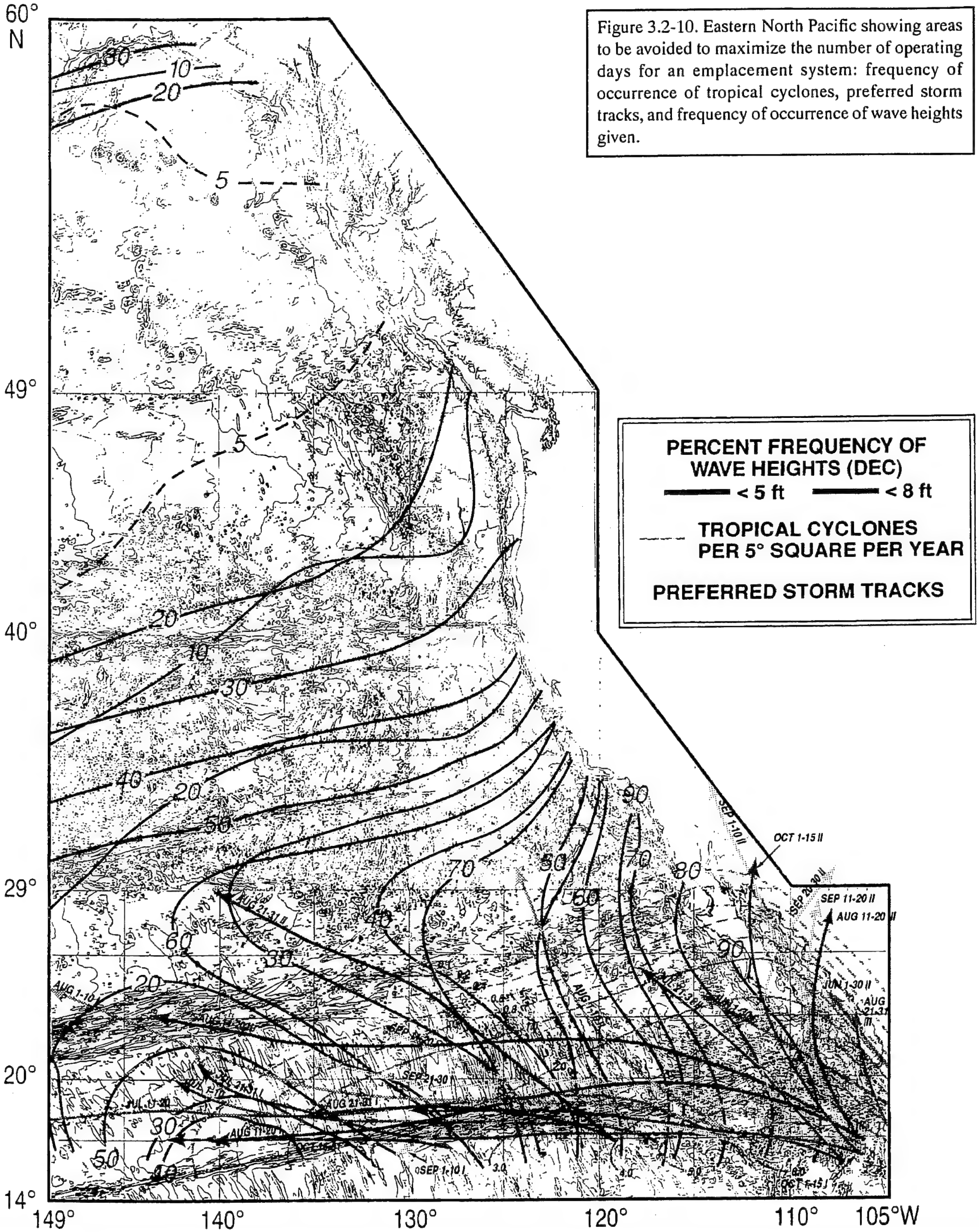


Figure 3.2-10. Eastern North Pacific showing areas to be avoided to maximize the number of operating days for an emplacement system: frequency of occurrence of tropical cyclones, preferred storm tracks, and frequency of occurrence of wave heights given.

Figure 3.2-11. Eastern North Pacific showing qualitative description of near-seafloor current speed.

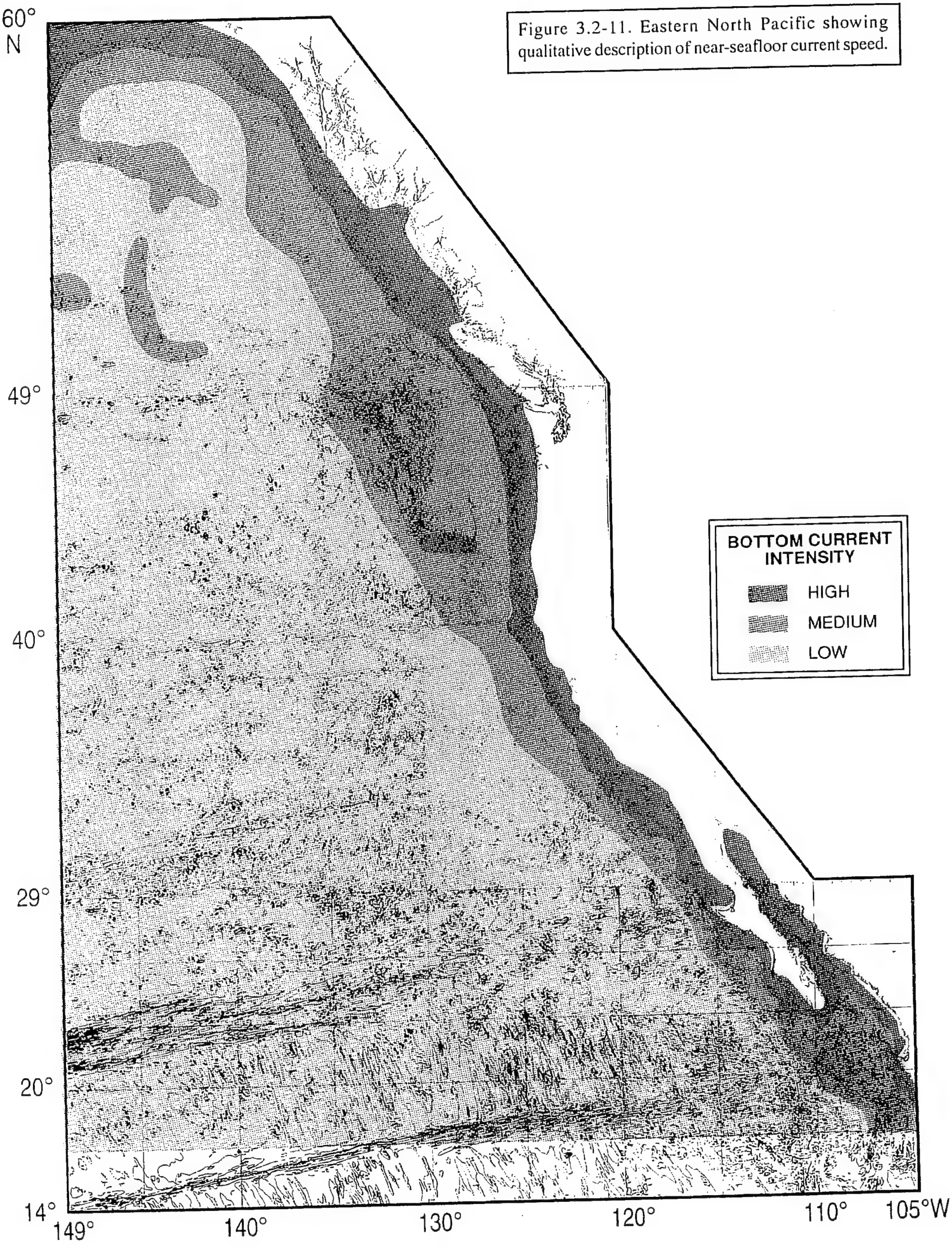
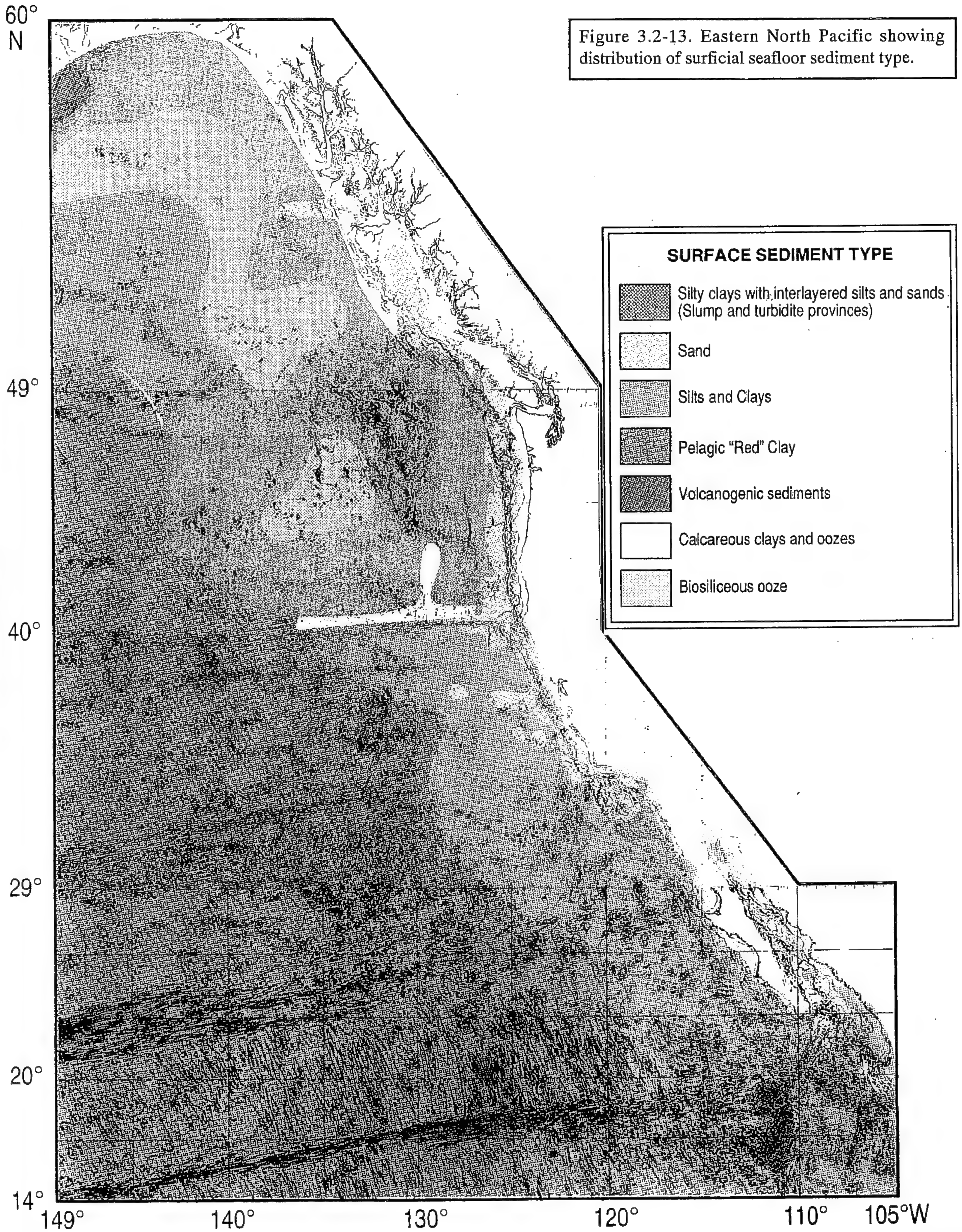


Figure 3.2-12. Eastern North Pacific showing distribution of potential seafloor resources (i.e., ferromanganese nodule fields).

Figure 3.2-13. Eastern North Pacific showing distribution of surficial seafloor sediment type.



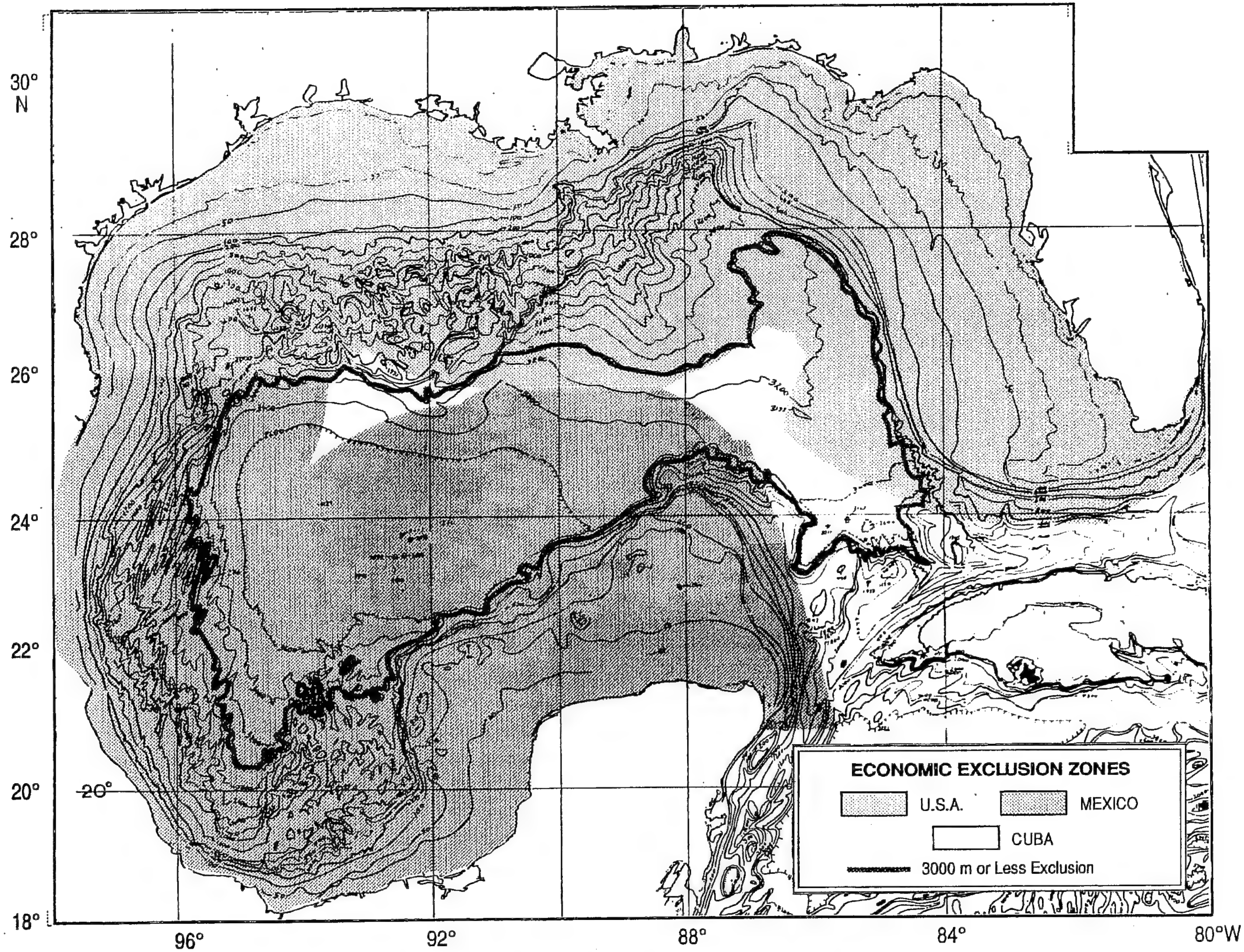


Figure 3.2-14. Gulf of Mexico with excluded areas shown, i.e., water depth <3000 m, foreign EEZs.

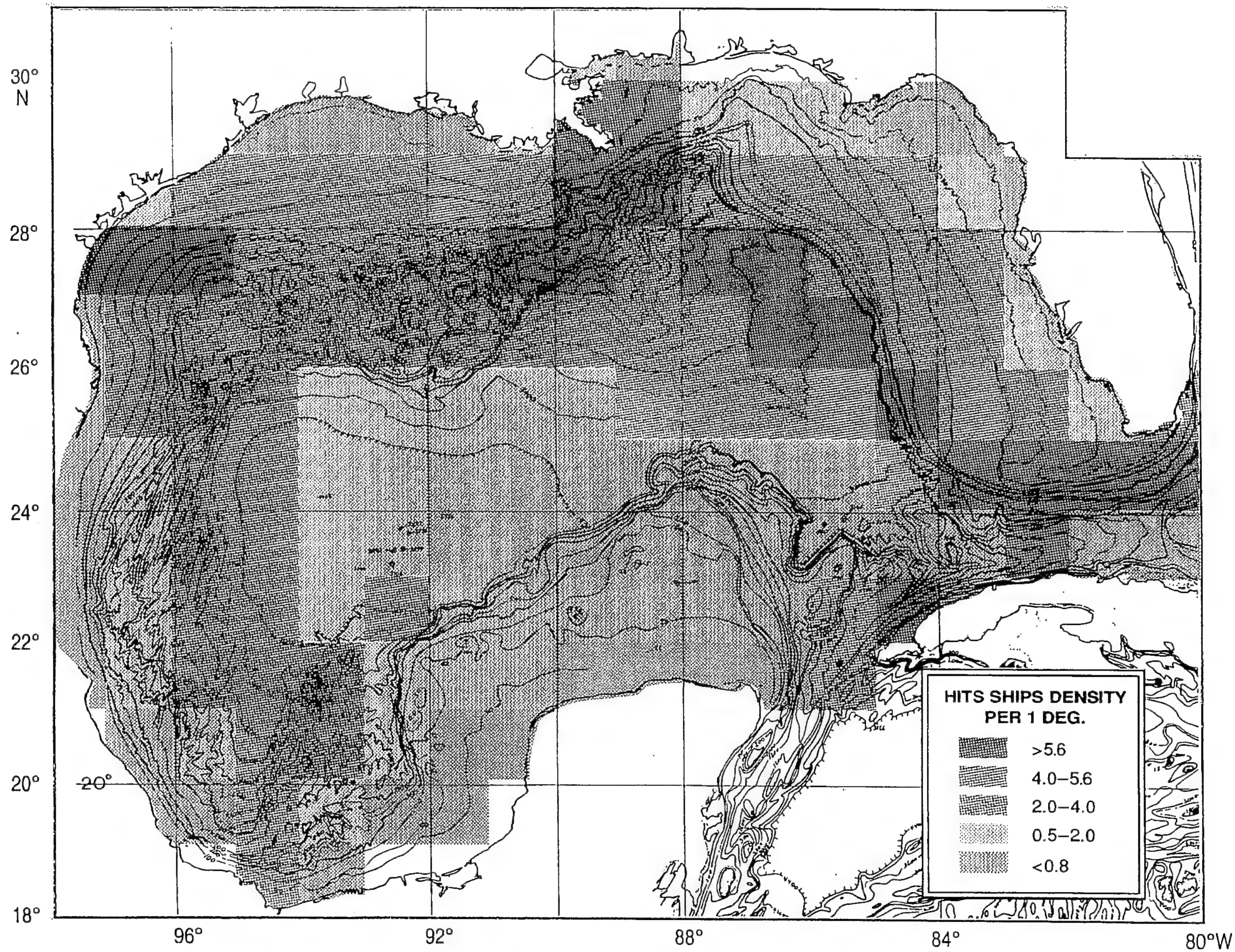


Figure 3.2-15. Gulf of Mexico showing areas to be avoided to minimize interference with ship traffic: data are numbers of ships per 1° × 1° area, from HITS Database.

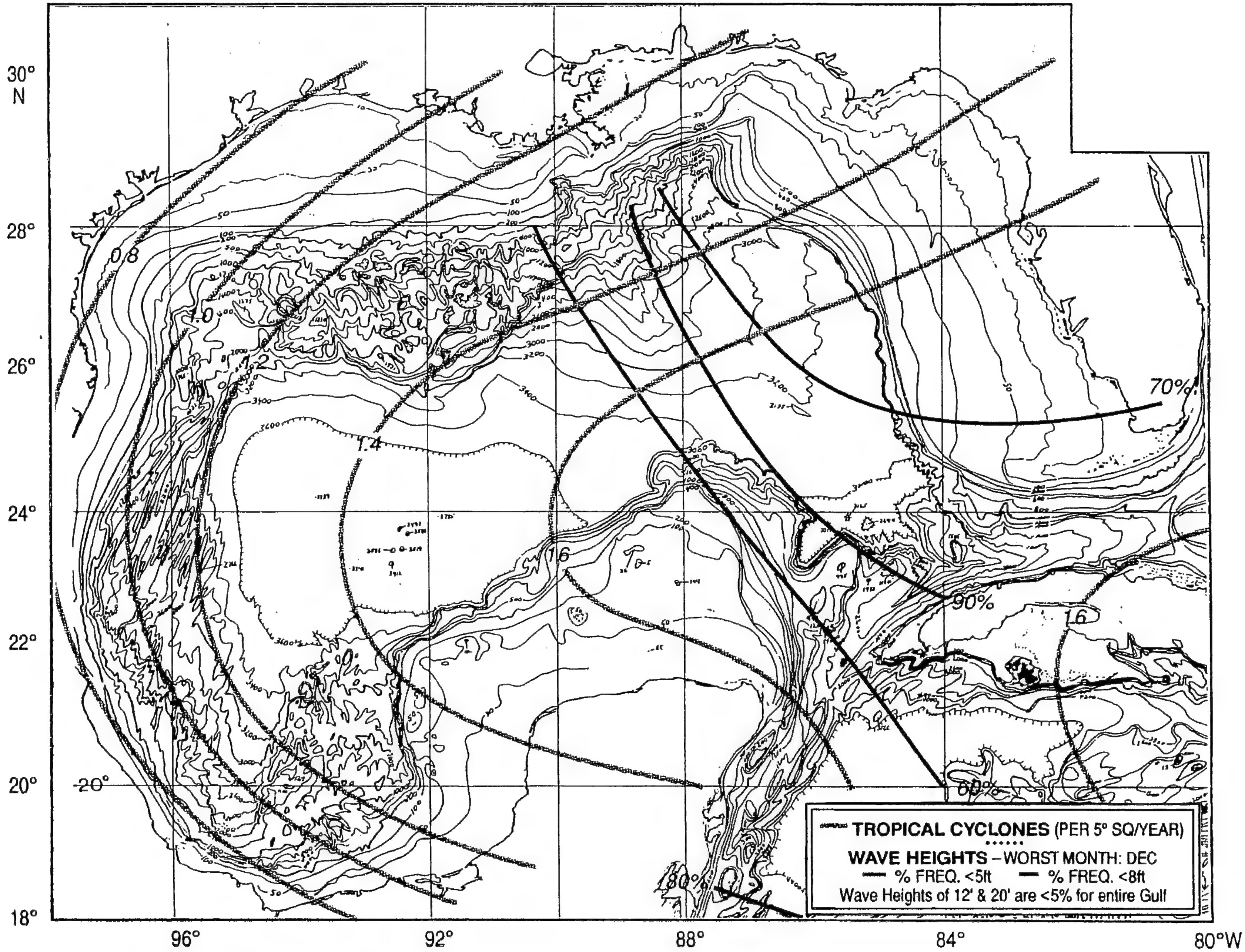


Figure 3.2-16. Gulf of Mexico showing areas to be avoided to maximize the number of operating days for an emplacement system: frequency of occurrence of tropical cyclones and frequency of occurrence of wave heights given.

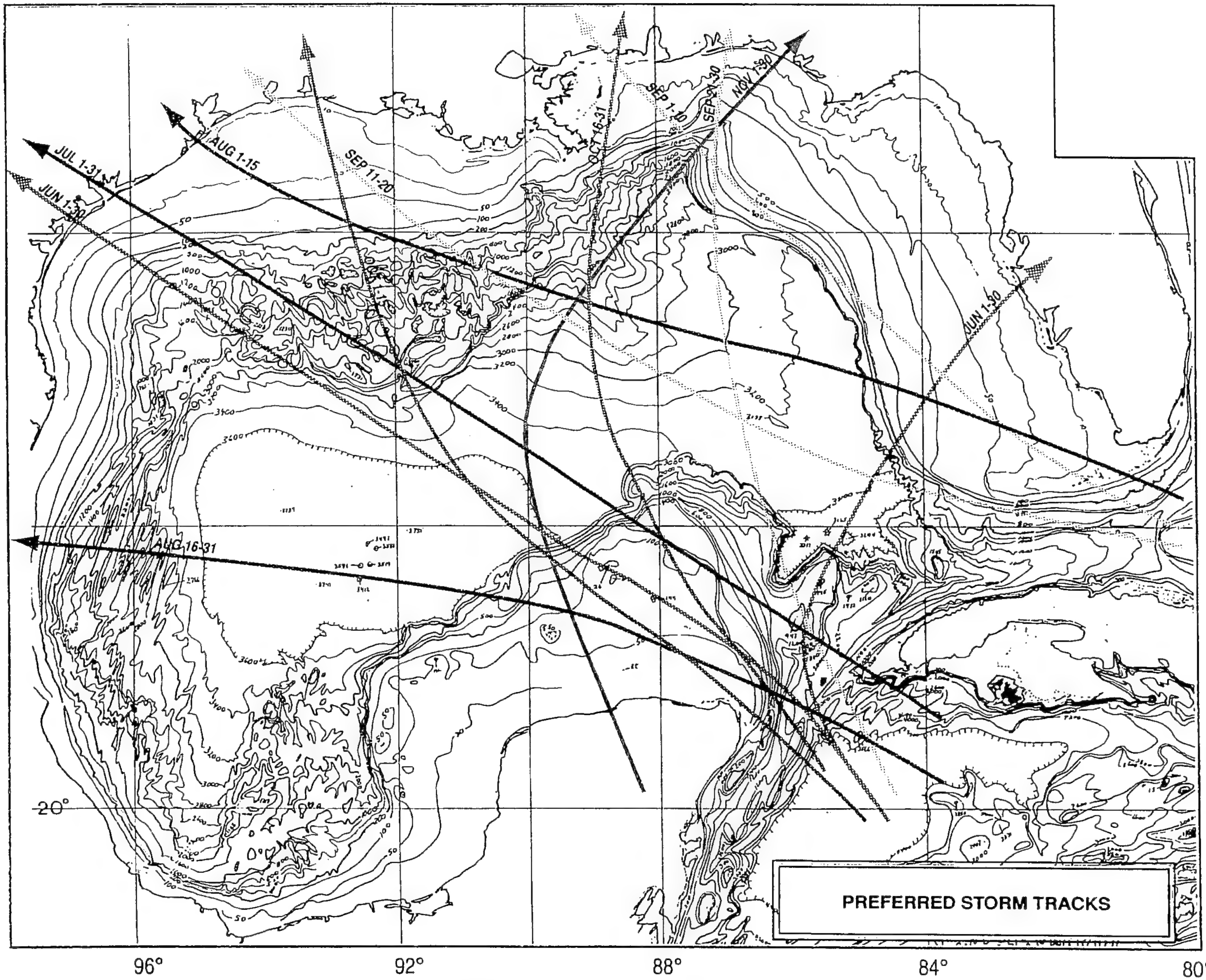


Figure 3.2-17. Gulf of Mexico showing areas to be avoided to maximize the number of operating days for an emplacement system: preferred storm tracks given.

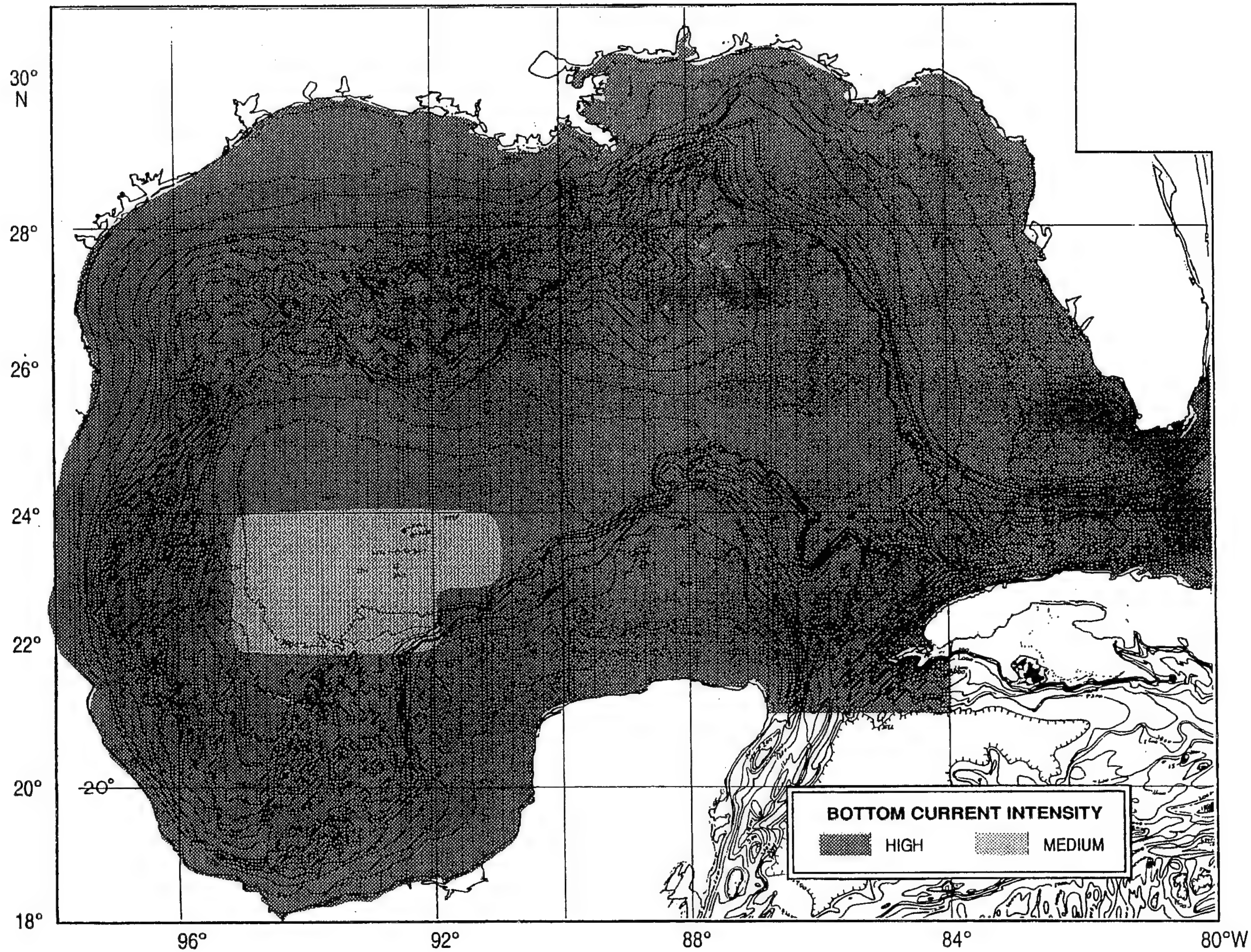


Figure 3.2-18. Gulf of Mexico showing qualitative description of near-seafloor current speed (note: no areas of "low" bottom current intensity).

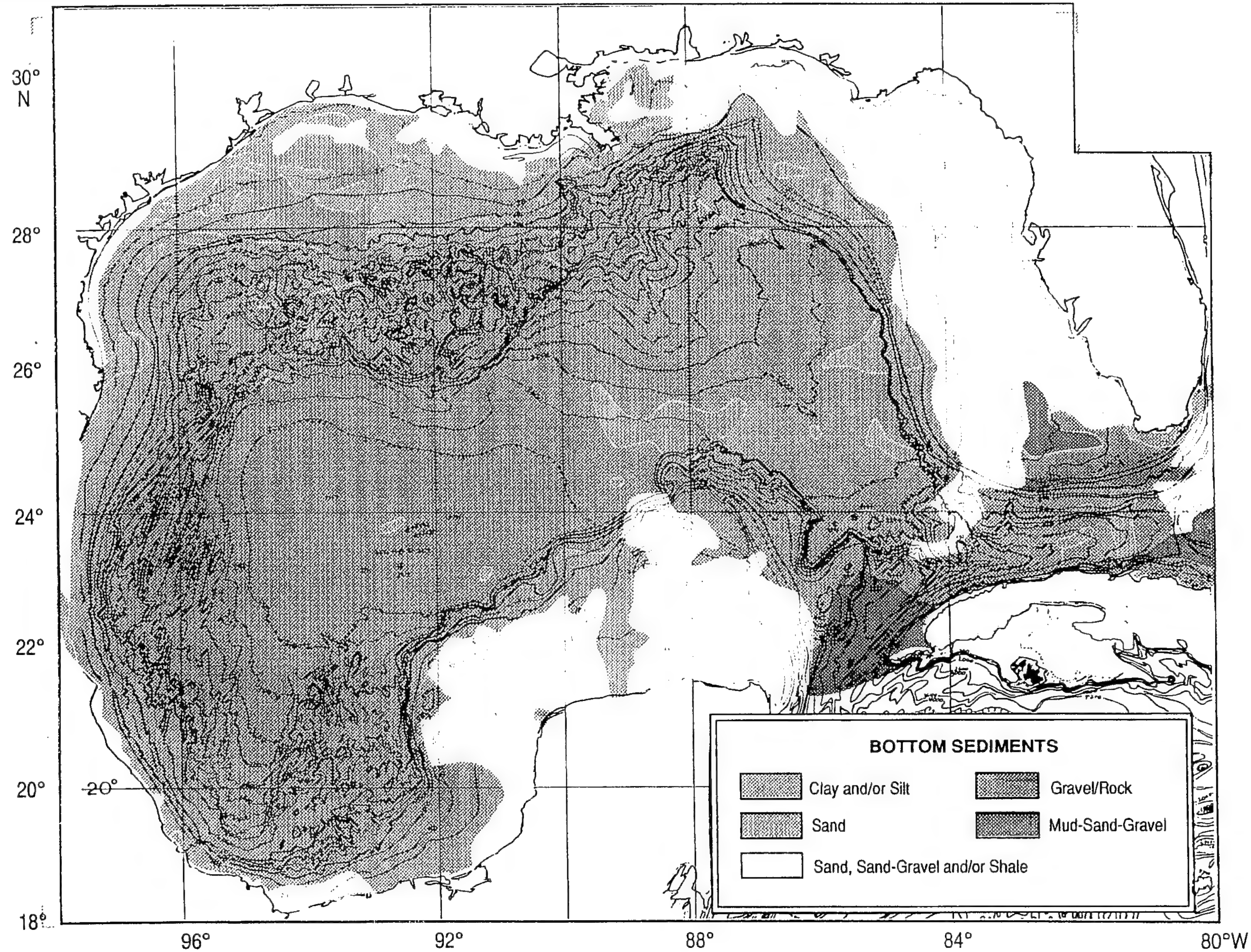


Figure 3.2-19. Gulf of Mexico showing distribution of surficial seafloor sediment type.

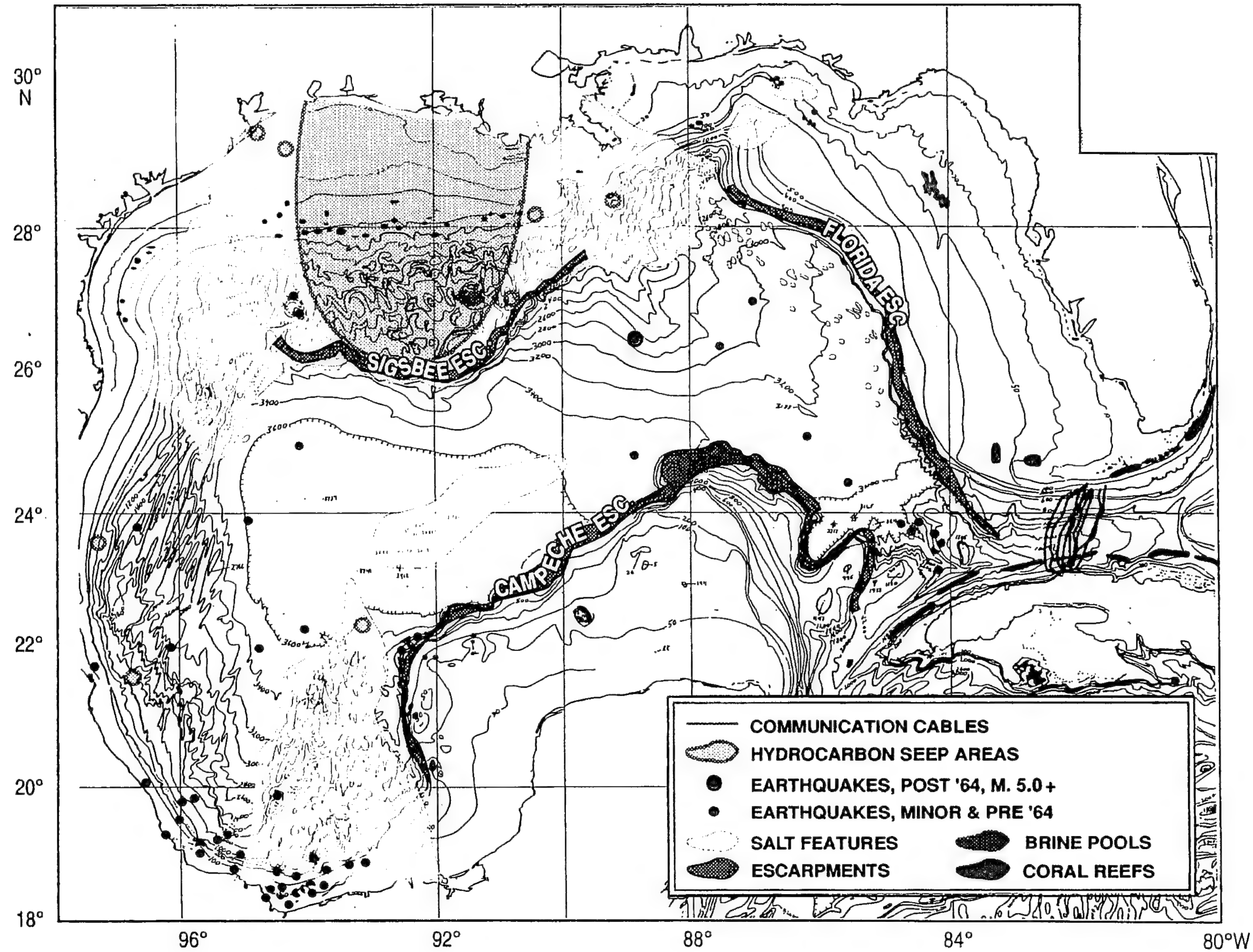


Figure 3.2-20. Gulf of Mexico showing areas to be avoided for waste isolation including communications cables, potential seabed resources, unique environments, and earthquakes.

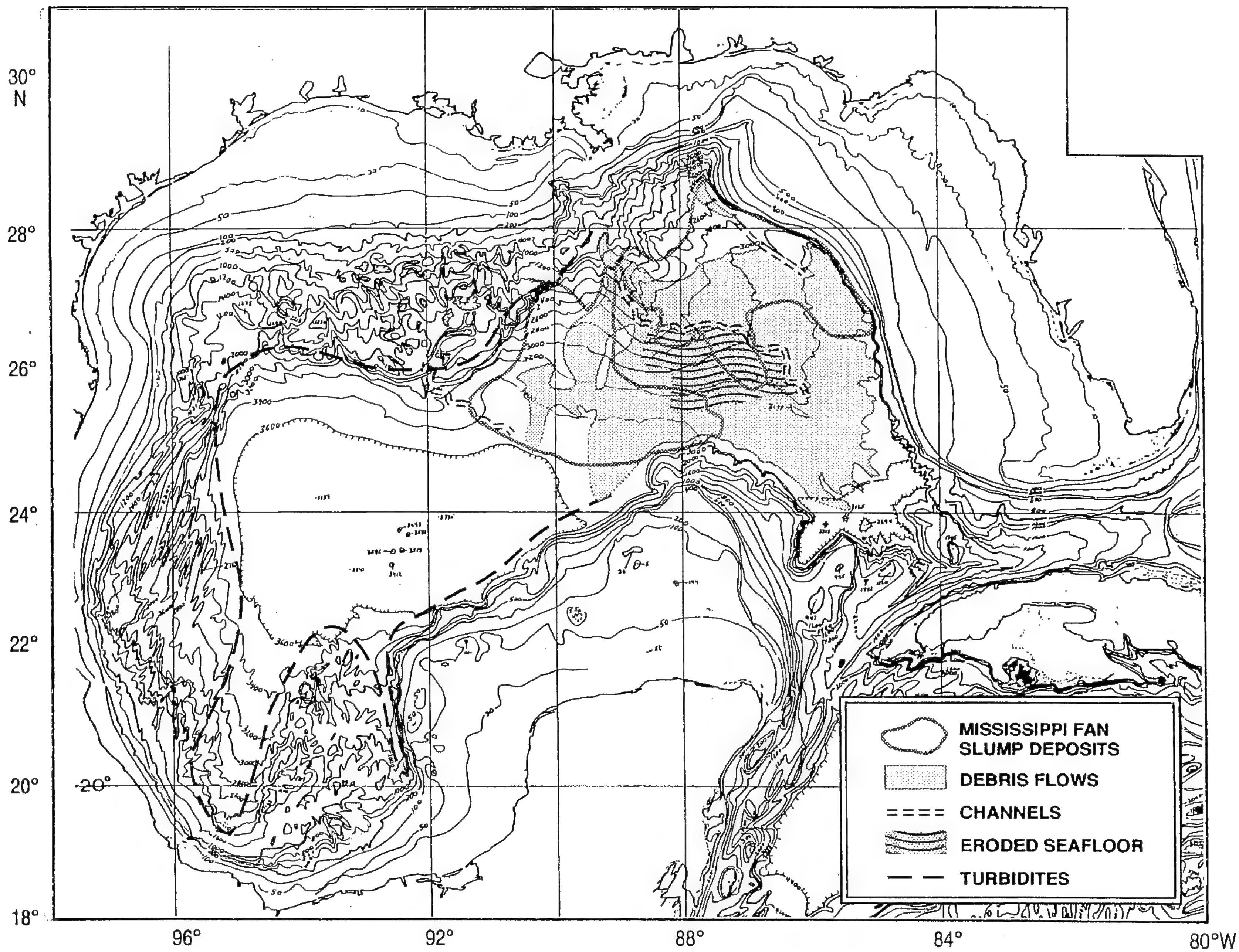


Figure 3.2-21. Gulf of Mexico showing areas to be avoided for waste isolation including areas of seafloor slumping, debris flows, and eroded sea floor.

The Surrogate Sites selected are an initial best estimate of either the most suitable or the most appropriate sites in each of the three abyssal ocean areas. Surrogate Site locations and water depths are listed in Table 3.2-4 and their locations illustrated in Figure 3.2-22. A brief description of each site and the rationale for its selection follows. Detailed information on the Surrogate Sites and their overall evaluation is given in Section 2.2, **Geology and Geophysics**, and Section 3.3.4, **(Site Selection) Model Scenarios and Results**.

Two Surrogate Sites were selected in the Atlantic. Atlantic-1 is located on the Hatteras Abyssal Plain at 28°N, 70°W. This site is characterized by a nearly flat, smooth seafloor (Fig. 3.2-2), low sedimentation rate (from interpretation of sediment type in Fig. 3.2-7) and biologic activity, relatively low bottom current activity (Fig. 3.2-5), a good weather regime (Fig. 3.2-4), and a low level of human activity (Fig. 3.2-3). Atlantic-2 is located at 27°N, 61°W, in a smooth-floored basin within a fracture zone (Fig. 3.2-2). The basin is connected to the Nares Abyssal Plain. This basin morphology is considered an advantage in that it may serve to restrict the dispersion of the waste material. Sedimentation rate (from interpretation of sediment type in Fig. 3.2-7) and biologic activity are extremely low, bottom current (Fig. 3.2-5) and weather regimes are favorable (Figs. 3.2-4 and 3.2-5), and the location is remote from human interference (Fig. 3.2-3). However, Atlantic-2 is also remote from U.S. ports; it is at the 1800-km (1000-nmi) limit set for cost effectiveness in this study.

Qualitative site selection in the midlatitude eastern North Pacific is a somewhat arbitrary exercise because of the uniformity of the region (Figs. 3.2-8, -9, -11, and -13). Beyond its narrow continental margin, the midlatitude eastern North Pacific is dominated by the abyssal hills and pelagic "red" clay province, which has a generally rolling morphology (Fig. 3.2-8), extremely low sedimentation rates (from interpretation of sediment type in Fig. 3.2-13) and biologic activity, and low levels of human activity (Fig. 3.2-9). Because no one area stood out as providing a significantly better site for waste isolation than any other, the two Pacific Surrogate Sites were chosen at locations where considerable oceanographic and biologic information is available. These sites are at Stations "F" and "G" of Smith et al. (1983). The benthic communities and associated biological and chemical measures at these stations have been studied on a continuing basis since 1978. Pacific-1 (Smith's "F"), located at 33.5°N, 124°W, is near the transition between the Monterey Submarine Fan and the abyssal hills. Pacific-2 (Smith's "G"), located at 35°N, 134°W, lies well within the abyssal hills and pelagic "red" clay province.

The Gulf of Mexico Surrogate Site, located at 25°N, 93.5°W, was selected in the western gulf on the northern Sigsbee Abyssal Plain and just outside the EEZ of Mexico (Fig. 3.2-14). The Gulf site occupies the smoothest seafloor (Fig. 3.2-14), with the lowest sedimentation rates (interpreted from sediment type in Fig. 3.2-19), accessible to the U.S. This location is qualitatively the best site for waste isolation in the Gulf of Mexico; however, the Gulf Surrogate Site is of lower desirability/quality than many potential sites in the Atlantic or Pacific.

Table 3.2-4. Surrogate Sites

Site	Latitude, °N	Longitude, °W	Depth, m
Atlantic 1	28	70	5200
Atlantic 2	27	61	6100
Gulf of Mexico	25	93.5	3600
Pacific 1	33.5	124	4600
Pacific 2	35	134	5100

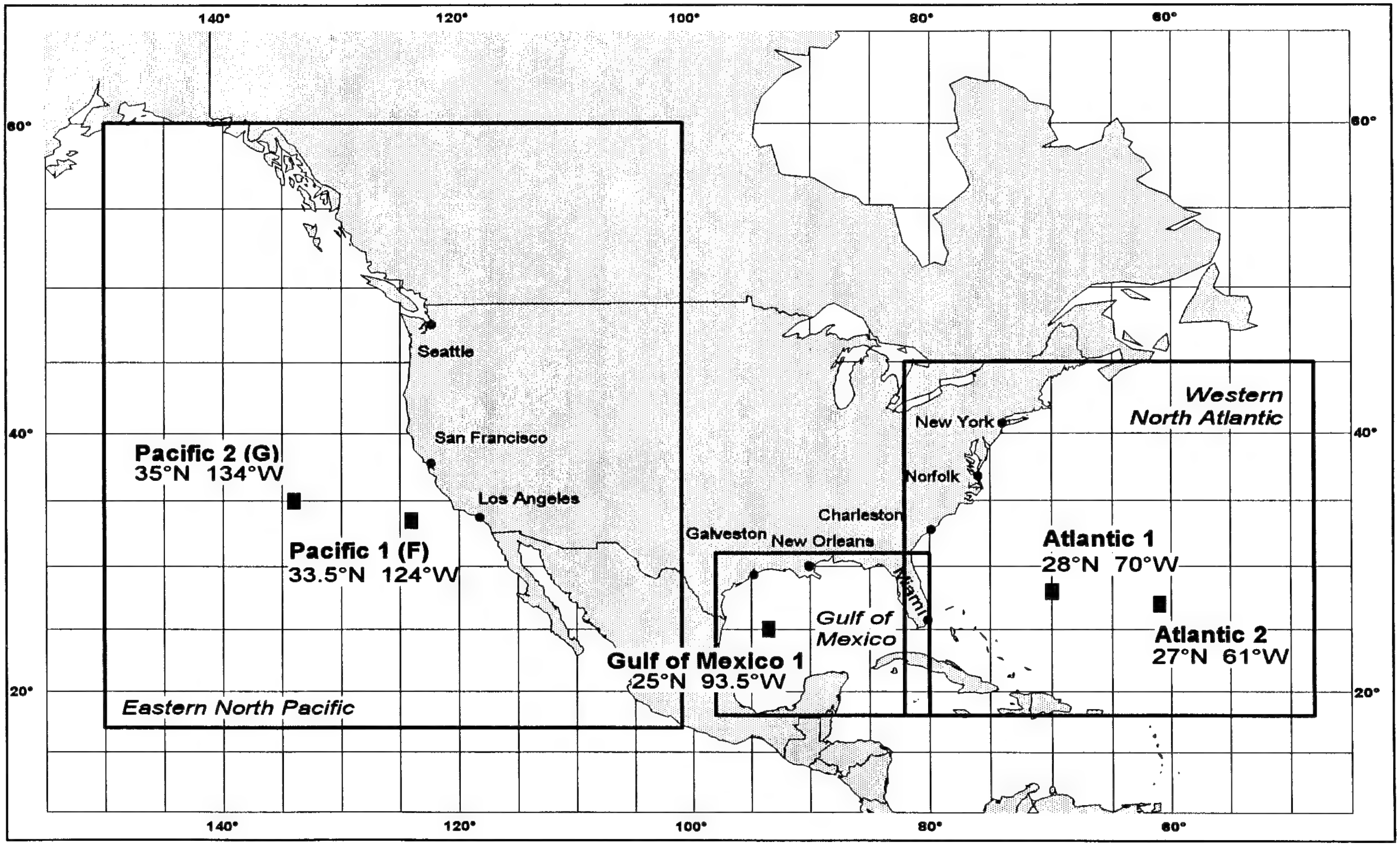


Figure 3.2-22. Areas of map overlays and locations of Surrogate Sites.

3.3 Site Selection Model *by Peter Fleischer*

3.3.1 Background and Approach

The problem of site selection, or the identification of optimal locations within a geographic area on the basis of a set of predefined criteria, is common to many scientific and technical endeavors. In the field of ocean-waste disposal and isolation, a large number of variables, from legal and technical constraints to the spectrum of conditions and processes that define the geo-, hydro-, and biospheres, will drive the site selection process. In simple cases, the variables affecting a site selection may be few, and the process becomes intuitive and self-evident. In most cases, however, many factors of varying significance and quality enter into the selection process and result in a perplexing and unmanageable situation. To make the site selection process workable, factors must be assessed in such a way that the process is documented, reproducible, and quantitatively expressed.

To quantify the site selection process, the concept of geographic screening or filtering has been followed for some time. In this approach, each variable, or factor, is presented as a geographically referenced layer that shows the distribution of allowed and prohibited attributes. The set of layers that corresponds to all factors then acts as a screen to remove areas with any undesirable attributes from consideration. This approach is readily adapted to digital geographic information systems (GIS). Such a GIS overlay screening has been developed for identifying shallow-water ocean-disposal sites for dredged material (Pequegnat 1984; Pequegnat et al. 1990). This implementation of the geographic layer screening approach is designed to address primarily the geographic distribution of definition and regulatory properties of the areas under consideration. These properties are exclusionary, that is, they define acceptable or unacceptable conditions. All environmental attributes, however, are not inherently exclusionary, and a means to register varying degrees of acceptability is required for a comprehensive assessment of large, complex geographic areas. Hollister (1991) provides, for an abyssal ocean-disposal option, a conceptual development for such a process with a "geographic filter" approach. In this approach, exclusionary and weighted attributes are used together in a set of shaded overlays such that their summation reveals optimum areas by the degree of "light shining through." Hollister emphasizes the importance of defining the assumptions that describe the desired conditions, that is, the scenario for which the geographic filter is designed.

The concept of geographic overlay of exclusionary and variable, weighted attributes is further developed and implemented in our Site Selection Model. Several steps are required to transform the overlay approach into a more general model. First, the weighting of attributes, or *factors*, must be performed not only *among* the set of factors, but also *within* each factor. Second, the factors and the values that distinguish their descriptions must be easily adjustable. Following these steps, the "shading" of each layer can be altered, and the relative "shading" within each layer can also be changed. For example, the factor of benthic biomass might be assigned a weight of 5% among the included factors; and in addition, desirably low values of biomass might be scored high, and less desirable biomass values might receive lesser scores. With this approach, the concept of a static geographic filter effectively becomes a dynamic representation, or model. Such a model allows, as inputs: (1) easy

addition of layers, (2) adjusting the importance, or *weighting*, of each *factor*, and (3) assigning a degree of desirability, or *score* to each value range, or *category*, of any factor. The model thus enables the entire site-selection attribute set of geographic overlays to be weighted and scored for site optimizations under various *scenarios*, such as, for instance, isolation or dispersal of waste material.

The implementation of the Site Selection Model is subject to a number of requirements and constraints. First, the model must be in digital form so that the necessary calculations can be executed rapidly by computer. Second, the model is intended as a large area, regional site selection tool that identifies optimal areas on the basis of generalized, regional attributes, such as those (but not exclusively) used in the mapping approach in Section 3.2. The optimal areas, as identified by the model, are then further examined and adjusted on a local basis as proposed in the initial Tier I regional compilation and survey of the Survey and Monitoring Plan described in Section 4.0. Third, the model must be easy to use and edit, and be open-ended, because project constraints required that model development, data entry, and scenario description be conducted essentially in parallel. Fourth, it should be robust, generic, and portable so that adaptations and transfers to other platforms are easy.

3.3.2 Description of Model

The Site Selection Model implements the principle of geographic overlay of variable factors within a commercial spreadsheet program. Instead of overlaying factor values directly, the model uses tables of factor values and combines them in a geographically referenced array to produce a gridded score-map of relative site desirability. Small- to intermediate-sized models of this type lend themselves well to a spreadsheet implementation. Current spreadsheet programs are capable of extensive linking and cell-referencing. These programs contain comprehensive function sets; their graphical user interfaces allow easy, rapid, large-scale on-screen editing, and their widespread acceptance makes dissemination of the models easy and virtually platform- and vendor-independent.

The structure and operation of the Site Selection Model is illustrated by following its process flow. All factors are initially assigned *weights*, and the weights normalized on a factor-weighting table. The factor weightings are referenced to a table of factor categories, where each factor category is assigned a *score*. This score is the desirability of the individual factor category with respect to the site selection scenario. The factor-category scoring table is used to calculate a *weighted score* for each category. For example, the set of weighted category scores for the factor of benthic biomass would be its 5% factor weighting multiplied by the numerical scores assigned to the value ranges of biomass. *Factor weights* and *category scores* are the fundamental user inputs to the model, and their manipulation is the basis of any scenario to be modeled. These tables contain a representation of all data entered into the model, but without reference to location.

Geographic referencing of the data, as weighted scores, is accomplished by gridding. Each area under consideration is divided into a georeferenced grid, with each grid cell corresponding to a spreadsheet cell. The real-world grid-cell size is arbitrary; for this work, grid cells are defined as 1° squares of latitude and longitude. Every factor entered into the

model is assigned its own set of georeferenced grid cells, and all grid-cell sets are stored in an array. Each grid cell is referenced to its appropriate weighted factor category in the category scoring table. This georeferenced grid-cell set forms a complete, geographic, weighted, and scored data representation.

The factor category scores are stored in the array so that they can be summed to produce a combined score for each grid cell, or 1° square. The set of combined grid-cell scores represents the output of the model. The score set is, in turn, referenced to map-simulating representations of spreadsheet cells for visualization of score distribution within each area, and for display in 2D and 3D contour-map-simulating surface graphs. In addition, grid-cell score sets from all areas can be combined for statistical analysis and for export to mapping or GIS applications.

A detailed functional description of the Site Selection Model is given below. It is followed by data entry and technical considerations.

3.3.2.1 Functional Description

It is evident from the above description that the Site Selection Model has three functional components, a front-end input section consisting of the factor weighting and scoring tables, a georeferenced database section, and an output section consisting of score sets and graphical and statistical representations. The model is constructed in a series of linked spreadsheets that follow the functional logic (Fig. 3.3.2-1). With smaller, linked spreadsheets instead of a single comprehensive spreadsheet, the model can be more easily modified and edited, and can be operated in sections. The weighting and scoring tables are on the front-end, or user-input spreadsheet. The front end is linked to each of three georeferenced database and score-computation spreadsheets, comprising the western North Atlantic, Gulf of Mexico, and eastern North Pacific areas. The databases are in turn linked to graphical displays for each area, and to a score export and single statistical analysis spreadsheet. The following sections describe the spreadsheet operations required for factor weighting and scoring, geographic referencing, score computation, and model outputs.

(1) Weighting and Scoring Tables

The weighting and scoring tables contain, in columnar format, all factor information, the weighting and scoring user inputs, and the formulas to produce the weighted factor-category scores. Figures 3.3.2-2 and 3.3.2-3 illustrate representative examples of the factor-weighting table, and of the factor-category scoring table, respectively. A linked weighting/ scoring worksheet (Fig. 3.3.2-1) provides a formatted printout of the weighting and scoring inputs.

(a) Factor Types

Three types of factors may be used in the model. These are exclusion factors, category factors, and continuous-range, fixed-score factors. The number of factors of each kind that may be included is limited only by computing capacity.

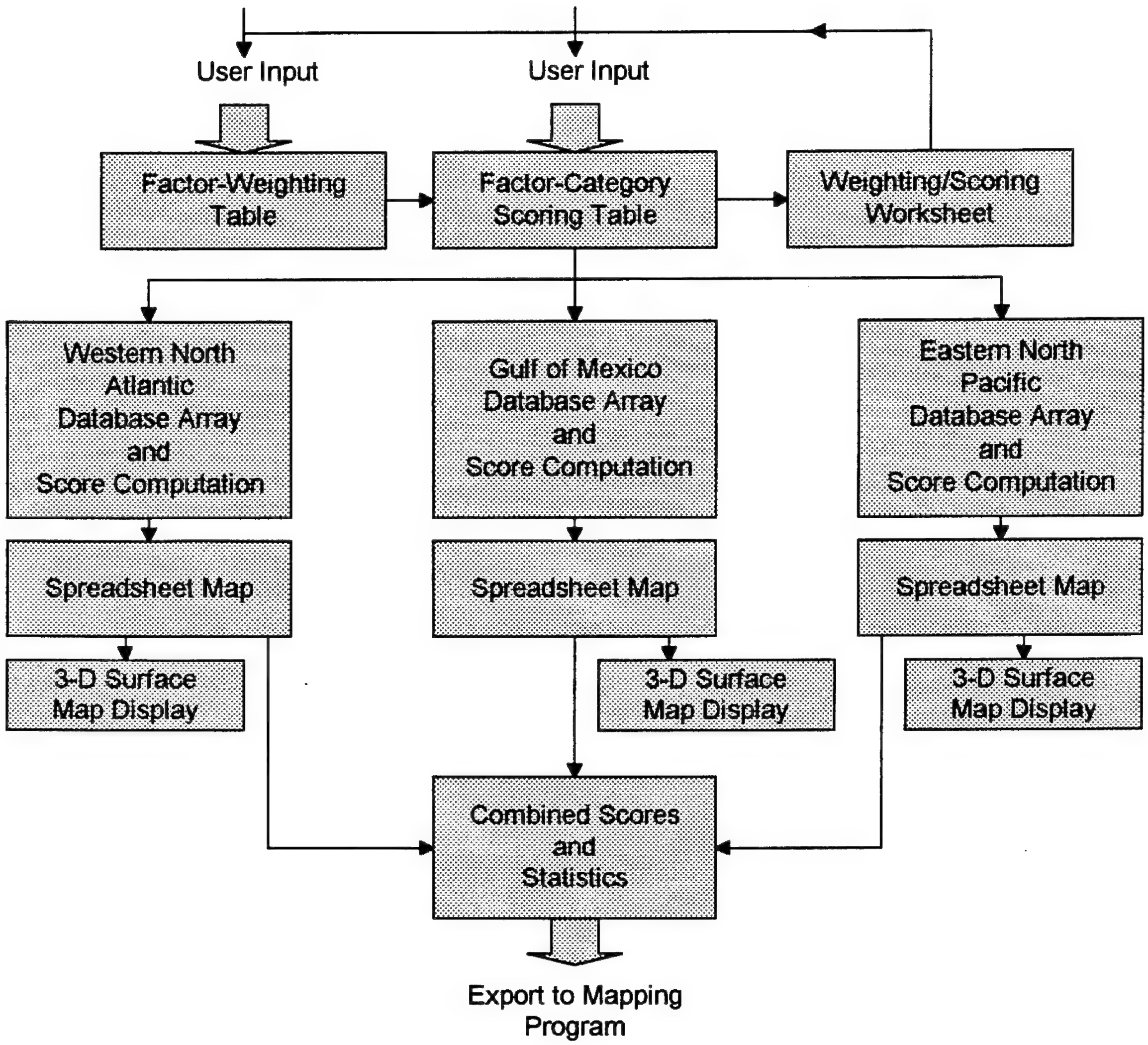


Figure 3.3.2-1. Flow Diagram of spreadsheet-based Site Selection Model, showing linked files and data flow.

FACTOR WEIGHTING TABLE

Partial View and Examples

#	Criterion	#	Factor	weight	% factor weight
			1-99 scorable 101-199 exclusion 201-299 fixed score	weight sum = 100 any no., or e = excluded	% sum = 100.00
—	testing	0	dummy	0	0.00
A	definition	101	1000 nm limit	e	none
B	unique environments	104	A: Bahama Platform	e	none
C	anthropogenic	1	HITS 1° ship density	5	5.00
D	geologic	2	max slope/5'x5', deg	7	7.00
"	"	"	"	"	"
G	oceanography	21	lyr 6 bottom curr speed	9	7.00
"	"	"	"	"	"
H	distance	201	NWA_New York	0	0.00
"	"	"	"	"	"

Figure 3.3.2-2. Example of a portion of the factor weighting table.

FACTOR CATEGORY SCORING TABLE

Partial View and Examples

#	**Factors** Categories	% factor weight	Value (for info only)	**Category Scores**	Weighted Factor Scores
	total # of factors = **41** **# of scorable factors =** **21**	total % = 100.00	may use for factor plots E = excluded	1-5 (5 = best, (1 = worst) -1000 = excl.	(- #) = excl
0	**dummy**	0.00	1	**3**	0.00
101	**1000 nm limit**	none	**E**	none	-1000.00
104	**Bahama Platform (WNA)**	none	**E**	none	-1000.00
1	**HITS 1° ship density**	5.00			
	<1 (<0.8 in GOM)		1	**5**	0.25
	1-2 (0.8-2 in GOM)		2	**3**	0.15
	>2		4	**2**	0.10
	2-4 (GOM)		4	**1**	0.05
	>4 (GOM)		8	**-1000**	-50.00
2	**max slope/5'x5', deg**	7.00			
	<0.25°		0.25	**5**	0.07
	0.25-<1°		1	**3**	0.14
	1-<5°		5	**2**	0.21
	>5°		16	**1**	0.35
21	**lyr 6 bottom curr speed**	7.00			
	0-0.25 cm/sec		1	**5**	0.07
	0.25-0.5		2	**4.5**	0.10
	0.5-1		3	**4**	0.14
	1-2		4	**3**	0.21
	2-4		5	**2**	0.28
	4-8		6	**1**	0.35
201	**WNA-New York, distance**	0.00	prop. to proximity	fixed	0.00

Figure 3.3.2-3. Example of a portion of the factor scoring table.

Exclusion factors operate on a yes/no basis; they need not be weighted and contain no scorable categories. Exclusion factors can be turned on or off by the user. Exclusion factors, when activated, are used to exclude, or remove from consideration, the geographic areas, or grid cells, that the factor describes. For example, the requirement of depth over 3000 m is incorporated as an exclusionary factor that, when activated, removes areas with depths under 3000 m from the scoring process.

Category factors are the principal factor type of the model; it is the scoring of categories that allows the user to model various scenarios. In addition to factor weights assigned by the user, factor categories contain two or more categories that can be scored for desirability by the user. A category factor can have a relative weight from 0% to 100% of the combined weight of all factors. A 0% weight removes the factor from use, and a 100% weight makes it the sole weighted factor. Factor categories represent the numerical ranges or the descriptive characteristics of each factor. Categories are the basis of the scoring scheme and make it possible for the user to assign arbitrary scores. The categories for each factor must be defined when the factor is installed in the model; that is, the continuum of values for the factor must be broken into a reasonable number of appropriate value ranges or categories. In the case of benthic biomass, for example, the range of existing values, from approximately 0.1 mg C/m^2 to 3000 mg C/m^2 is broken into 10 half-log value ranges, or categories. The user can then score the value categories presented by the model. Scoring is accomplished with an arbitrary but consistent set of numbers. In this model, for reasons related to graphical display, scores must be from 1 to 5, with 1 corresponding to the least desirable condition, a "zero" or a grade of "F," and 5 corresponding to the most desirable condition, a "100" or an "A." Scores need not be integers, and any category can accept any permissible score. Individual categories can also be made exclusionary by assigning them a large negative number, as explained in a following section.

Continuous-range factors have their full range of values preserved. They are weightable, like category factors, but are not scorable by the user. Instead, scoring is expressed as a value-dependent function. The function, in effect, calculates an internal score that is combined with the factor weight for the final weighted score. The functions can be linear or any other type. Distances are the only factors currently entered as continuous-range factors. The continuous-range factors provide the advantage of high-definition continuous scores, instead of the stepped scores of the category factors, but at the expense of the user's ability to assign scores as desired.

(b) Factor Weighting

The process of factor weighting is illustrated by the factor-weighting table (Fig. 3.3.2-2). The first two columns identify the subject criteria by which the factors are grouped, the third column identifies the factor type by number, and the fourth column lists the factors by description. The fifth, or weight column is for user entry. Factor weights are entered here, either as percent values or as arbitrary numbers. Weights are summed at the top of the column. Exclusion factors are activated by entering an "e" in the weight column. Factor weighting is normalized as weight percent in the right column with the formula:

$$\% \text{ factor weight} = 100 \text{ (weight/weight sum)}$$

As a check, the % factor weights are summed at the top of the column.

A dummy factor is entered at the top of the table. The dummy factor is used only for testing and diagnosis of the model, and for displaying exclusion factors independently. The dummy factor is not activated in normal use of the model.

(c) Category Scoring

Weighted category scoring is illustrated on the scoring table (Fig. 3.3.2-3). The first column identifies each factor by number. The second column names each factor and lists the factor categories where they apply. The third column simply references the percentage factor weights from the weighting table. The fourth, or value column, is for information only, and lists suggested values that may be used to plot single factors. The values are not scores, but represent the actual values of the factors. The fifth, or category scores column, is for user entry. Category scores from 1 to 5 are entered here. Categories may be excluded by entering –1000 or other appropriately large negative numbers. There are no user entries for exclusion or continuous-range (distance) factors. Weighted factor scores are calculated in the right column. For category factors the formula is:

weighted factor score = (% factor weight) (category score)

For continuous-range (distance) factors, because the scoring is internal, the formula reduces to:

weighted factor score = 0.01 (% factor weight)

For exclusion factors, the formula uses an IF statement:

weighted factor score = IF (factor excluded by "e" in factor weight column) is

TRUE, return (–1000)

FALSE, return (0)

The weighted factor scores in this column are linked to the grid cells of the database.

(2) Georeferenced Database and Score Computation

Geographic referencing is accomplished by gridding the geographic areas. The 1° square grid size used here is a compromise among resolution, the general quality of existing areal data coverage for the abyssal seafloor, and simple computing requirements. Figure 3.3.2-4 shows the grid for the Gulf of Mexico. Latitude and longitude are given for the 1° square centers. Similar grids for the Atlantic and Pacific regions are shown in Appendix A. Grid cells are numbered consecutively. Only the active grid cells are numbered and included in the database; land and out-of-area waters are included in displays only. The size of the gridded areas is defined by a 1000-nmi distance from the continental United States. The numbers of active grid cells for the Atlantic, Gulf of Mexico, and Pacific areas are 779, 160, and 1302, respectively, for a total of 2241.

The grid cells for the Atlantic, Gulf of Mexico, and Pacific areas are each entered into separate spreadsheets and arranged in columnar format to create the database arrays (Fig. 3.3.2-5). The first two columns of the database array contain latitude and longitude

lt/lg	97.5	96.5	95.5	94.5	93.5	92.5	91.5	90.5	89.5	88.5	87.5	86.5	85.5	84.5	83.5	82.5	81.5	80.5
30.5									85	95	105	115						
29.5				29	41	53	64	75	86	96	106	116	125	133	141			
28.5	1	9	19	30	42	54	65	76	87	97	107	117	126	134	142	148		
27.5	2	10	20	31	43	55	66	77	88	98	108	118	127	135	143	149		
26.5	3	11	21	32	44	56	67	78	89	99	109	119	128	136	144	150	154	
25.5	4	12	22	33	45	57	68	79	90	100	110	120	129	137	145	151	155	158
24.5	5	13	23	34	46	58	69	80	91	101	111	121	130	138	146	152	156	159
23.5	6	14	24	35	47	59	70	81	92	102	112	122	131	139	147	153	157	160
22.5	7	15	25	36	48	60	71	82	93	103	113	123	132	140				
21.5	8	16	26	37	49	61	72	83	94	104	114	124						
20.5		17	27	38	50	62	73	84										
19.5		18	28	39	51	63	74											
18.5				40	52													

Figure 3.3.2-4. Georeferenced 1° square grid cell set for the Gulf of Mexico. Latitudes and longitudes refer to the centers of the 1° squares.

GULF OF MEXICO

1° CELL WEIGHTED FACTOR SCORES AND CELL SCORES

					Factor Number:							Distance Table
lat	**lon**	**cell#**	**SCORE**	**% SCO.**	**0**	**101**	**106-8**	**1**	**2**	**21**	**205**	**nm**
					dum	1K nm	xcl fts	HITS	slope	lr 6 curr	N.O. dist	N. O.
28.5	-97.5	**1**	**0**	**0**	0			0.25	0.35	0.269995	0	419.331
27.5	-97.5	**2**	**0**	**0**	0			-50	0.35	0.269995	0	419.331
26.5	-97.5	**3**	**0**	**0**	0			0.25	0.35	0.269995	0	445.41
"	"	"	"	"	"	"	"	"	"	"	"	"
27.5	-95.5	**20**	**0**	**0**	0		-1000	-50	0.14	0.404992	0	322.678
26.5	-95.5	**21**	**0**	**0**	0		-1000	0.05	0.14	0.404992	0	354.968
"	"	"	"	"	"	"	"	"	"	"	"	"
25.5	-93.5	**45**	**3.65**	**66.25**	0			0.15	0.14	0.449991	0	323.434
24.5	-93.5	**46**	**3.84**	**71.12**	0			0.15	0.35	0.404992	0	374.622
"	"	"	"	"	"	"	"	"	"	"	"	"
24.5	-80.5	**159**	**0**	**0**	0		-1000	-50	0.14	0.179996	0	605.616
23.5	-80.5	**160**	**0**	**0**	0			0.25	0.07	0.449991	0	641.523

Figure 3.3.2-5. Example section of a georeferenced database array with computed scores and lookup table for the continuous-value factor of distance.

for the grid cells entered in the third column. The fourth and fifth columns contain the scoring computations. The following columns are the geographically referenced, weighted scores for all factors. Each geographically referenced cell score is linked to its appropriate factor category in the scoring table (Fig. 3.3.2-3). This is the structure that allows the user to arbitrarily weight and score each factor on a geographic, areal basis. The grid cell columns of continuous-value (distance) factors, in addition to being linked to the scoring table, contain the scoring function. The distance factors are scored linearly and proportional to proximity to port of egress, that is, the score decreases from 5.0 at the port to 0.0 at a distance of 1000 nmi, with greater distances excluded. A grid-cell lookup table of values is required for the continuous-value factors, in this case distances. This table is to the right of the database array. The score for continuous-value factors (distance) is calculated by:

Distance weighted-score = IF (grid-cell distance is >1000) is
TRUE, return (–1000)
FALSE, return ((factor weighting) (((1000 grid-cell distance)/1000) 4) + 1))

The final georeferenced grid-cell score computation, shown in the fourth column of Figure 3.3.2-5, consists of summing the weighted scores for all factors in the database array:

grid-cell score =

(SUM (weighted factor scores) + ABS.VAL.(SUM (weighted factor scores)))/2,

where ABS.VAL. is the absolute value of the quantity. This score formula calculates a score in the range of 1 to 5. Exclusion factors and excluded categories, scored with large negative values, produce a score of zero. A conversion to a percent score is done in the fifth column of Figure 3.3.2-5 with the formula:

grid-cell % score = 12.5 ((grid-cell score – 1) + ABS.VAL.(grid-cell score – 1))

With this computation, grid cell scores are between zero and 100, and exclusions are also zero.

(3) Model Outputs

The fundamental model output is the set of gridded scores for each geographic area. The scores can be viewed as a gridded geographic display within the spreadsheet, exported to a mapping program, or subjected to statistical analysis.

Figure 3.3.2-6 shows an example of a spreadsheet score map of the Gulf of Mexico. A score map resides in each of the georeferenced database spreadsheets. The 160 active cells for the Gulf of Mexico are referenced to the score computation in the database array. Numbers in the shaded, inactive land and ocean areas are for display with the internal graphing functions of the spreadsheet program. An example of a spreadsheet-based, 3D surface graph of the Gulf of Mexico is shown in Figure 3.3.2-7.

LAT/ LON	98.5	97.5	96.5	95.5	94.5	93.5	92.5	91.5	90.5	89.5	88.5	87.5	86.5	85.5	84.5	83.5	82.5	81.5	80.5	79.5
31.5	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	0	0
30.5	-18	-18	-18	-18	-18	-18	-18	-18	-18	0	0	0	0	-18	-18	-18	-18	-18	0	0
29.5	-18	-18	-18	-18	0	0	0	0	0	0	0	0	0	0	0	0	-18	-18	0	0
28.5	-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-18	-18	0
27.5	-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-18	-18	0
26.5	-18	0	0	0	0	0	0	0	60	60	0	0	0	0	0	0	0	0	-18	0
25.5	-18	0	0	0	0	66	66	66	69	69	58	54	67	0	0	0	0	0	0	0
24.5	-18	0	0	0	0	71	0	0	0	0	0	0	0	71	58	0	0	0	0	0
23.5	-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.5	-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-18	-18	-18	-18	-18
21.5	-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-18	-18	0	-18
20.5	-18	-18	0	0	0	0	0	0	0	-18	-18	-18	0	0	0	0	0	0	0	0
19.5	-18	-18	0	0	0	0	0	0	-18	-18	-18	-18	0	0	0	0	0	0	0	0
18.5	-18	-18	-18	-18	0	0	-18	-18	-18	-18	-18	0	0	0	0	0	0	0	0	0
17.5	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	0	0	0	0	0	0	0	0	0

Percent scores (0 = excluded, or 0 score)

EXAMPLE SCENARIO

latitude/longitude at centers of 1° squares

Figure 3.3.2-6. Example of spreadsheet score-map for the Gulf of Mexico. White cells, active area; light gray cells, other waters; dark gray cells, land.

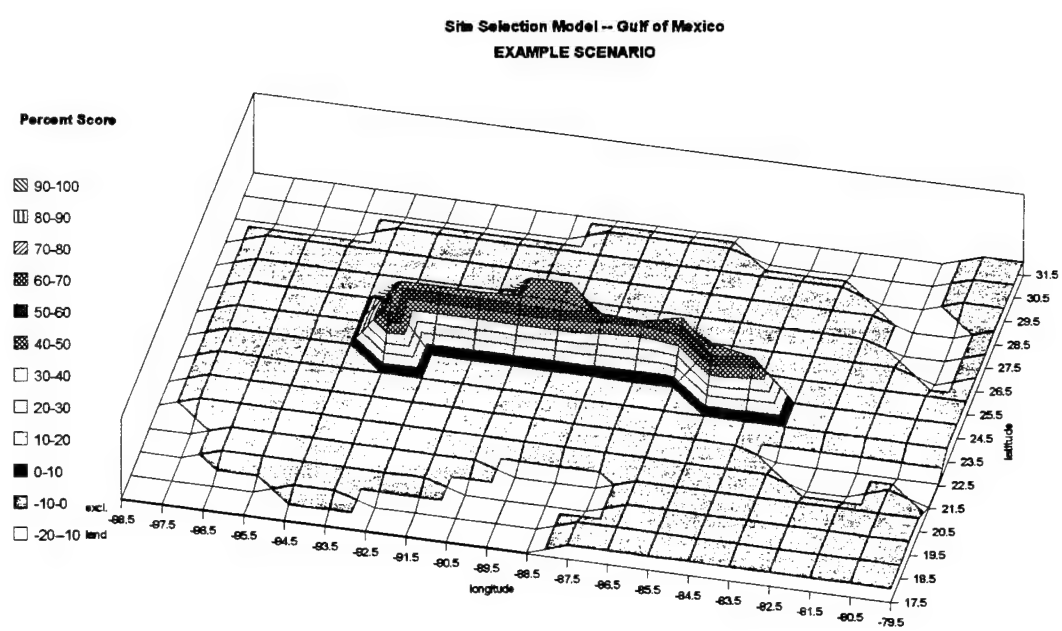


Figure 3.3.2-7. Example of spreadsheet-based a three-dimensional score map.

For statistics and for export, the cell scores computed in the three georeferenced database spreadsheets are linked to a single, statistics spreadsheet. All cell scores are listed in one column in this spreadsheet. Most statistics can be calculated at this point with the built-in functions of the spreadsheet program, including histograms of cell scores.

The single combined score column is also the point of export to other applications. A mapping program, for example, is used to provide a true geographic display of 1° scores in this report.

3.3.2.2 Data Entry

The bulk of the work in building the model for a particular region is in the conversion of the areal data contained in the factors into categorized, georeferenced grid cells. Two types of data can be used, map data or digital data.

To convert map data to grid cells, grid-cell maps (Fig. 3.3.2-4) can be used as plotting sheets. The process consists of drawing a grid onto the paper map, and then marking the cells on the plotting sheet with colors that correspond to the value range, or category, of the factor being entered from the map. The categories on the color-coded plotting sheet are then entered into the database array by their cell references to the scoring table. Data entry is facilitated by rapid "drag and drop" copying of multiple cells, and by "filling" cell selections, as made possible by the graphical interface of the spreadsheet program.

Data in digital format, when provided in the appropriate geographic grid size, are easier than map data to enter. Digital data can be readily sorted into proper cell sequence, and various data types can be combined into the desired data format. Examples are conversion of current speeds into vectors, and computing depth-dependent regressions for benthic biomass. If the gridded data are in the form of a range of real number values, the data can be broken into ranges, or categories, with a nested IF statement in a formula that returns the appropriate scoring sheet cell reference for each category. Eight levels of nesting are typically permissible in spreadsheet formulas.

3.3.2.3 Technical Considerations

The Site Selection Model, as described above, operates in Microsoft Excel, Version 4.0, running in Microsoft Windows 3.1. The machine is an AT-compatible, VESA Local Bus microcomputer with an Intel 486DX33 CPU and 20 MB of RAM. The model size, with 41 factors currently entered, is about 5.5 MB in 9 files. All files can be run together; they can also be run in subsets or singly. When the model is run in its entirety, the weighting and scoring tables and the three 3D graphs can be displayed together on the screen and the database files placed in the background. This approach allows the user to weight, score, and view the results graphically for all areas. Ultimate model size is limited by spreadsheet size and RAM. The Excel spreadsheet is 256 columns by 16,384 rows, equivalent to a 2048 × 2048 matrix; thus the model is well under this limit. On a machine with limited RAM, the model can be run in sections. No concerted effort was made to reduce file sizes, although size reductions in the database array might be achieved by a formula-naming

function, which would substitute for a large number of linked cell references and formulas. The model as constituted should translate to other commercial spreadsheet programs with functions similar to Excel, and to Macintosh or other machines for which graphical spreadsheet programs exist.

Map illustrations of Site Selection Model scenarios in the following sections were produced by importing the georeferenced grid-cell scores into the thematic mapping program MapViewer. A set of 1° square boundary files was created for the 2241 active cells of the three areas and linked to a data file containing the imported grid-cell score sets. The 1° scores were then combined with a land mass overlay on a Miller projection map of the entire area.

3.3.3 Factors Entered into Model

The model contains a total of 41 factors, including 11 exclusion factors, 21 category factors having a total of 123 scorable categories, and 9 distance factors. To facilitate weighting and scoring, the factors are divided into 8 functional criterion groups. The criterion groups are (1) definition, (2) unique environments, (3) anthropogenic, (4) geologic, (5) biologic, (6) weather, (7) oceanographic, and (8) distance. Table 3.3.3-1 summarizes the criteria and factors, and Table 3.3.3-2 summarizes the category scores for the scorable factors. A number of additional factors are available in 1° square digital format, but were not entered into the model (Table 3.3.3-3). The additional factors are presently considered redundant, incomplete, or of limited value for site selection. The following sections describe the 41 active factors entered into the model, and include the rationale and justification for each factor. Factor descriptions are summarized in Table 3.3.3-4, and data sources for each factor are referenced in Table 3.3.3-5. Table 3.3.3-5 also serves as the general citation reference to all following subsections on factor descriptions, where the sources are not individually cited; and the table should be consulted for each section. Factors are cross-referenced by number in the tables and in the following sections.

As stated elsewhere in this report, it is again emphasized that the compilation of appropriate and sufficient factors for site selection is a compromise dictated by the time and resources available for this task. An effort was made to compile relevant factors that could be obtained and processed quickly, and to ensure that all site selection criteria were adequately represented. In some instances, alternate and potentially better data sources or additional factors might improve the accuracy of the model. However, for other factors, the paucity of measurements and observations on the abyssal seafloor reduces the data quality to generalized estimates. The absence of some potentially important factors does not indicate that they were ignored, but that they were not used at this stage due to the above mentioned constraints.

3.3.3.1 Definition Factors

Definition factors are derived from the initial conditions and limitations for area assessment as set forth in the proposal for this project. They include a 1000-nmi maximum

Table 3.3.3-1. Site Selection Model: Factor Weightings.

No.	Criterion	total weight percent: SCENARIO isol.	disp.	logis.	No.	Factor	weight percent: SCENARIO isolation	dispersal	logistics
A	**Definition** *excluded or included (e, i)*				101	1000 nm limit	e	e	i
					102	foreign EEZ	e	e	e
					103	<3000 m	e	e	e
B	**Unique Environments** *excluded or included (e, i)*				104	A: Bahama Platform	e	e	i
					105	A: Puerto Rico Trench	e	e	i
					106	G: Florida Escarpment	e	e	i
					107	G: Campeche Escarpment	e	e	i
					108	G: Salt Structures	e	e	i
					109	P: East Pacific Rise	e	e	i
					110	P: Mendecino F Z	e	e	i
					111	P: Gorda / J.d Fuca Ridge	e	e	i
C	**Anthropogenic**	*10*	*10*	*10*	1	HITS 1° ship density	5	5	10
					14	1° cable density	5	5	0
D	**Geologic**	*26*	*26*	*0*	2	max slope/5'x5', deg	7	7	0
					10	5'x5' "roughness" (s.d.)	3	3	0
					6	sediment accum. rate	1	1	0
	treated as exclusionary:				11	manganese nodules	0.001	0.001	0
					12	sediment provinces	15	15	0
	treated as exclusionary:				13	abundant earthquakes	0.001	0.001	0

Table 3.3.3-1, continued. Site Selection Model: Factor Weightings.

No.	Criterion	total weight percent SCENARIO isol.	disp.	logis.	No.	Factor	weight percent SCENARIO isolation	dispersal	logistics
E	Biologic	20	28	0	3	benthic O2 flux	5	7	0
					4	sediment organic C %	5	7	0
					5	organic C burial rate	5	7	0
					19	benthic biomass	5	7	0
F	Weather	15	15	40	7	tropical cyclones	5	5	20
					8	wave height frq <5 ft	3	3	10
					9	wave height frq >12 ft	7	7	10
G	Oceanographic	29	21	0	15	major currents, locations	3	2	0
					16	1° eddy density	5	3	0
					17	surface current speed	0	0	0
					18	bottom current intensity	9	7	0
					20	layer 1 surface speed	3	2	0
					21	layer 6 bottom curr. spd.	9	7	0
H	Distance	0	0	50		distance weight:	0	0	50
					201	NWA-New York	0	0	50
					202	NWA-Norfolk	0	0	0
					203	NWA-Charleston	0	0	0
					204	NWA-Miami	0	0	0
					205	GOM-New Orleans	0	0	50
					206	GOM-Galveston	0	0	0
					207	ENP-Los Angeles	0	0	50
					208	ENP-San Francisco	0	0	0
					209	ENP-Seattle	0	0	0

Table 3.3.3-2. Site Selection Model: Factor-Category Scores.

No.	Factor	Factor-Categories	category scores: SCENARIO isolation	dispersal	logistics
1	HITS 1° Ship Density	<1 (<0.8 in GOM)	5	5	5
		1-2 (0.8-2 in GOM)	3	3	3
		>2	2	2	2
		2-4 (GOM)	1	1	1
		>4 (GOM)	-1000	-1000	-1000
2	Max. Slope of 5'x5' Square	0-<0.25°	5	1	0
		0.25-<1°	3	2	0
		1-<5°	2	3	0
		>5°	1	5	0
3	Benthic Oxygen Flux	<0.06 mol / m2 yr	5	1	0
		0.06-0.24	4	2	0
		0.24-0.6	2	4	0
		>0.6	1	5	0
4	Sed. Org. Carbon Content	<0.25 % (wt / wt)	5	1	0
		0.25-0.5	4	2	0
		0.5-1.0	3	3	0
		1-2	2	4	0
		>2	1	5	0
5	Org. Carbon Burial Rate	<0.5 mmol / m2 yr	5	1	0
		0.5-2	4	2	0
		2-5	3	3	0
		5-10	2	4	0
		>10	1	5	0
6	Sediment Accum. Rate	<0.25 mg / cm^2 yr	5	1	0
		0.25-0.5	4	2	0
		0.5-1.0	3	3	0
		1-2	2	4	0
		>2	1	5	0
7	Tropical Cyclones	<0.1 no / 5° square yr	5	5	5
		0.1-0.4	4	4	4
		0.4-1.0	3	3	3
		1.0-2.0	2	2	2
		>2.0 (ENP)	-1000	-1000	-1000

Table 3.3.3-2, continued. Site Selection Model: Factor-Category Scores.

No.	Factor	Factor-Categories	category scores		
			SCENARIO		
			isolation	dispersal	logistics
8	Wave Height frq <5 ft	0-20 %	1	1	1
		20-40	2	2	2
		40-60	3	3	3
		60-80	4	4	4
		80-100	5	5	5
9	Wave Height frq >12 ft	0-5 %	5	5	5
		5-20	3	3	3
		20-50	1	1	1
		50-100	-1000	-1000	-1000
10	5'x5' "Roughness"	0-10 std dev, m	5	1	0
		10-40	4	2	0
		40-160	3	3	0
		160-640	2	4	0
		>640	1	5	0
11	Manganese Nodules	absent	1	1	0
		present	-10^7	-10^7	0
12	Sediment Provinces	WNA pelagic clay	5	1	0
		WNA calcareous ooze	3	1	0
		WNA calcareous marl	4	1	0
		WNA calcareous clay	5	1	0
		WNA silty clay	3	3	0
		WNA silt	1	5	0
		WNA sand	1	5	0
		GOM mud (clay &/or silt)	5	1	0
		GOM mud-sand	2	4	0
		GOM sand, incl. sd., grv. &/or shell	1	5	0
		GOM gravel, rock	1	5	0
		GOM mud-sand-gravel	1	5	0
		ENP pelagic "red clay"	5	1	0
		ENP biosiliceous ooze	3	1	0
		ENP calcareous ooze	3	1	0
		ENP volcanogenic sediments	1	4	0
		ENP terrigenous silt and clay	3	3	0
		ENP slump & turbidite deposits	2	4	0
		ENP terrigenous sands	1	5	0

Table 3.3.3-2, continued. Site Selection Model: Factor-Category Scores.

No.	Factor	Factor-Categories	category scores		
			SCENARIO		
			isolation	dispersal	logistics
13	Abundant Earthquakes	absent	1	1	0
		present	-10^7	-10^7	0
14	1° Cable Density	0 no. per square (active)	5	5	0
		1	4.5	4.5	0
		2	4	4	0
		3	3.5	3.5	0
		4	3	3	0
		5	2.5	2.5	0
		6	2	2	0
		7	1.5	1.5	0
		8	1	1	0
		9	1	1	0
15	Major Currents, Locations	Gulf Stream, mean pos. (NWA)	1	5	0
		Gulf Stream, extreme pos.(WNA)	2	4	0
		Loop Current (GOM)	1	5	0
		none (incl. ENP)	5	1	0
16	1° Eddy Density	<1 no. per square (WNA)	5	1	0
		1	4	2	0
		2, 3	3	3	0
		4, 5, 6, 7	2	4	0
		>7	1	5	0
		low (GOM, ENP)	5	1	0
		medium (GOM)	2	4	0
		high (GOM)	1	5	0
17	Surface Current Speed	not computed	0	0	0
		0- 5 cm/sec	0	0	0
		5-10	0	0	0
		10-20	0	0	0
		20-30	0	0	0
		>30	0	0	0
18	Bottom Current Intensity	low	5	1	0
		medium	3	3	0
		high	1	5	0

Table 3.3.3-2, continued. Site Selection Model: Factor-Category Scores.

No.	Factor	Factor-Categories	category scores: SCENARIO isolation	dispersal	logistics
19	Benthic Biomass	3162-10^3 mg C/m^2 (.5 log units)	1	5	0
		1000-3162	1	5	0
		316-1000	1	5	0
		100-316	2	4	0
		32-100	2.5	3.5	0
		10-32	3	3	0
		3.2-10	4	2	0
		1-3.2	5	1	0
		0.32-1	5	1	0
		0.1-0.32	5	1	0
20	Layer 1 Surface Current Speed	0-5 cm/sec	5	1	0
		5-10	4	2	0
		10-20	3	3	0
		20-40	2	4	0
		40-80	1	5	0
		>80	1	5	0
21	Layer 6 Bottom Current Speed	0-0.25 cm/sec	5	1	0
		0.25-0.5	4.5	1.5	0
		0.5-1	4	2	0
		1-2	3	3	0
		2-4	2	4	0
		4-8	1	5	0

Table 3.3.3-3. Other Factors Available in 1° Square Format (Not entered into Site Selection Model).

No.	Criterion	Factor
D	geologic	mean depth, 1° square
D	geologic	median depth, 1° square
D	geologic	max. depth, 1° square
D	geologic	min. depth, 1° square
D	geologic	slope angle, 1° square
D	geologic	dip of slope, 1° square
D	geologic	minimum slope angle of 5'x5' subsquares
D	geologic	number of subsquares with slopes <0.25°
D	geologic	mean depth, for 5'x5' subsquares with slopes <0.25°
D	geologic	standard deviation of depth for 5'x5' subsquares with slopes <0.25°
E	biologic	chlorophyll-A, NASA-GSFC global pigment database (incomplete)
G	oceanography	wave height frequency <8 ft
G	oceanography	wave height frequency >20 ft
G	oceanography	surface current direction
G	oceanography	current direction, layer 1, 2, 3 ,4, 5, 6
G	oceanography	current speed, layer 2, 3, 4, 5

Table 3.3.3-4. Site Selection Model: Factor Descriptions.

NO.	FACTOR	DESCRIPTION
1	HITS 1° Ship Density	Annual avg., instantaneous no. of ships per 1° square.
2	Maximum Slope of 5'x5' Square	Max. slope angle of 5'x5' subsquare within 1° square.
3	Benthic Oxygen Flux	mol/m2 yr, extrapolated from data bases for WNA and ENP. Derived from depth-dependent regression equation from observations for GOM. Depth for 1° square is mean depth from DBDB5.
4	Sediment Organic Carbon content	Percent (wt/wt) (see Factor 3).
5	Organic Carbon Burial Rate	$mmol/m^2yr$ (see Factor 3).
6	Sediment Accumulation Rate	g/cm^2 1000 yr or mg/cm^2 yr (see Factor 3).
7	Tropical Cyclones	Number of tropical cyclones per 5° square per yr.
8	Wave Height frequency >5 ft	Frequency % of wave heights <5 ft during worst month (December or January).
9	Wave Height frequency >12 ft	Frequency % of wave heights >12 ft during worst month (December or January).
10	5'x5' "Roughness"	Standard deviation in meters of sea data within 1° square (normally 144 points in 5'x5' subsquares).
11	Manganese Nodules	Presence or absence of ferromanganese nodules.
12	Sediment Provinces	Surficial sediment province or type. Note that classifications for the Atlantic, Gulf, and Pacific are different, and each must receive its own set of factor scores.
13	Abundant Earthquakes	1° squares with more than 2 or 3 earthquake. epicenters. This factor affects only the eastern N. Pacific; earthquake occurrences in the western North Atlantic and Gulf of Mexico are very low.
14	1° Cable Density	Number of working submarine communications cables per 1° square.
15	Major Currents, Locations	Center positions of Gulf Stream, Florida Current, and Loop Current; extreme positions of Gulf Stream.
16	1° Eddy Density	In WNA: number of eddies per 1° square observed per decade. In GOM and ENP: Estimated eddy density (high, medium, low) on scale comparable to WNA.
17	Surface Current Speed	Geostrophic speed, cm/sec in winter at surface, GDEM data. Layer thickness: WNA, 2000 m; GOM, 800 m; ENP, 1000 m. Model speeds were reported at 1.0° lat-lon intersections. They are transposed 0.5° NW to coincide with x.5° lat-lon intersections (1° square centers).

Table 3.3.3-4, continued. Site Selection Model: Factor Descriptions.

NO.	FACTOR	DESCRIPTION
18	Bottom Current Intensity	Estimated bottom current speed and frequency. High: mean speed >15 cm/sec, and/or maximum speed >25 cm/sec, >1 per year. Medium: mean speed 5 - 15 cm/sec, and/or maximum speed <25 cm/sec, <1 per year. Low: mean speed <5 cm/sec, and/or maximum speed <25 cm/sec, <<1 per year. Estimates based on compilation of bottom current measurements, photographic observations, topographic effects, and eddy kinetic energy calculations.
19	Benthic Biomass	Benthic macrofaunal biomass, mg Carbon/m^2, based on depth-dependent regression equations from observations. Depth for 1° square is mean depth from DBDB5.
20	Layer 1 Surface Current Speed	Surface current speed, cm/sec , from NRL Layered Circulation Model, layer 1. Initial thickness, ENP = 135m.
21	Layer 6 Bottom Current Speed	Bottom current speed, cm/sec , from NRL Layered Circulation Model, layer 6. Initial thickness, ENP = 5450m.
101	1000 nm Distance from CONUS	Approximate measurements from maps.
102	Foreign EEZ	A 200 nm exclusion zone.
103	3000 m Minimum Depth	3000 m contour.
104	WNA Bahama Platform	1° squares occupied about 80% by feature.
105	WNA Puerto Rico Trench	(see factor 104)
106	GOM Florida Escarpment	(see factor 104)
107	GOM Campeche Escarpment	(see factor 104)
108	GOM Salt Structures	(see factor 104)
109	ENP East Pacific Rise	(see factor 104)
110	ENP Mendecino F Z	(see factor 104)
111	ENP Gorda / Juan de Fuca Ridge	(see factor 104)
201	NWA-New York	Great circle distance in nautical miles from the designated ports to the center of 1° squares.
202	NWA-Norfolk	(see factor 201)
203	NWA-Charleston	(see factor 201)
204	NWA-Miami	(see factor 201)
205	GOM-New Orleans	(see factor 201)
206	GOM-Galveston	(see factor 201)
207	ENP-Los Angeles	(see factor 201)
208	ENP-San Francisco	(see factor 201)
209	ENP-Seattle	(see factor 201)

Table 3.3.3-5. Site Selection Model: Data Sources for Factors.

NO.	SOURCE
1	Planning Systems, Inc. 1994. Navy Standard Historical Temporal Shipping Database (HITS).
2	Vogt, P. R. 1994. DBDB5 analysis.
3	a) Jahnke, R. A. 1994. Data bases and original analysis. b) Vogt, P. R. 1994. DBDB5 analysis.
4	(see factor 3)
5	(see factor 3)
6	(see factor 3)
7	Crutcher, H. L. and R. G. Quayle. 1974. Mariners worldwide climatic guide to tropical storms at sea. Commander, Naval Weather Service Command, NAVAIR 59-1C-61. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.
8	a) Naval Oceanography Command Detachment, Asheville, N.C. 1985. U. S. Navy hindcast spectral ocean wave model climatic atlas: North Pacific Ocean. Commander, Naval Oceanography Command, NAVAIR 50-1C-539. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 329 pp. b) Naval Oceanography Command Detachment, Asheville, N.C. 1983. U. S. Navy hindcast spectral ocean wave model climatic atlas: North Atlantic Ocean. Commander, Naval Oceanography Command, NAVAIR 50-1C-538. Superintendent of Documents, U.S Government Printing Office, Washington, D.C. 375 pp.
9	(see factor 9)
10	Vogt, P. R. 1994, DBDB5 analysis.
11	(see factor 12 a, b)
12	a) Rona, P. A. 1980. The central North Atlantic Ocean basin and continental margins: Geology, Geophysics, geochemistry, and resources, including the Transatlantic Geotraverse (TAG). National Oceanic and Atmospheric Administration, NOAA Atlas 3, 99 pp. b) National Oceanic and Atmospheric Administration. 1985. Gulf of Mexico Coastal and Ocean Zones Strategic Assessment: Data Atlas. c) McCoy, F. W. and C. Sancetta. 1985. North Pacific sediments. In A. E. M. Naim, F. G. Stehli and S. Uyeda, eds. The Ocean Basins and Margins, Volume 7A: The North Pacific Ocean, Plenum Press, New York. p. 1-64. d) Frazer, J. Z., D. L. Hawkins and G. Arrhenius. 1972. Surface sediments and topography of the North Pacific, 1:3,630,000. Scripps Institution of Oceanography, Geologic Data Center. Charts 1-10.
13	Atwater, T. and J. Severinghaus. 1988. Tectonic map of the North Pacific Ocean. In E. L. Winterer, D. M. Hussong, and R. W. Webster, eds. The Eastern Pacific Ocean and Hawaii. The Geological Society of America, The Geology of North America, v. N, plates 3B, 3C.
14	a) American Telephone and Telegraph Company and International Cable Protection Committee. (various dates). Working telephone cables. Navigation Chart Overprints and Cable Route Maps Bedminster, NJ and London. b) National Oceanic and Atmospheric Administration. 1985. Gulf of Mexico Coastal and Ocean Zones Strategic Assessment: Data Atlas. c) Cable and Wireless (Marine) Ltd. 1994. Cable Route Listings and Maps for North Atlantic and North Pacific. Chelmsford, Essex, England. d) Pacific Telecom Cable, Inc. 1994. Cable Route Listings and Maps for North Pacific. Vancouver, Canada.

Table 3.3.3-5 continued. Site Selection Model: Data Sources for Factors.

NO.	SOURCE
15	a) Lybanon, M., R. L. Crout, C. H. Johnson and P. Pistek. 1990. Operational altimeter-derived oceanographic information: The NORDA GEOSAT Ocean Applications Program. Journal of Atmospheric and Oceanic Technology, v. 7, p. 357-376.
	b) Koshlyakov, M. N. 1986. Eddies of the western boundary currents. In V. M. Kamenkovich, M. N. Koshlyakov and A. S. Monin, Synoptic Eddies in the Ocean, D. Reidel Publishing Co., Dordrecht, ch. 4, p. 208-264.
16	a) Pistek, P. 1994. Personal communication.
	b) (see factor 15 b)
17	Pistek, P. 1994, Geostrophic circulation model , NRL/Stennis.
18	a) Fleischer, P. and F. A. Bowles. 1994. Original interpretation.
	b) Schmitz, W. J., Jr. 1984. Abyssal eddy kinetic energy in the North Atlantic. Journal of Marine Research, v.42, p. 509-536.
	c) Schmitz, W. J., Jr. 1988. Exploration of the eddy field in the middle latitude North Pacific. Journal of Physical Oceanography, v.18, p. 459-468.
	d) Vogt, P. R. and B. E. Tucholke. 1989. North Atlantic Ocean Basin; aspects of geologic structure and evolution. In A. W. Bally and A. R. Palmer, eds., The Geology of North America - An Overview. The Geological Society of America, The Geology of North America, v. A , p 53-80.
19	a) Rowe, G. T. 1994. Original analysis.
	b) Vogt, P. R. 1994. DBDB5 analysis.
20	Gallacher, P. C. 1994. NRL Layered Circulation Model. NRL/Stennis.
21	Gallacher, P. C. 1994. NRL Layered Circulation Model. NRL/Stennis.
101	(see Factor 103)
102	a) NOAA, NOS, 1992, Catalog 5, Bathymetric Mapping Products
	b) Ross, D. A., and J. Fenwick. 1992. Maritime claims and scientific research jurisdiction. International Maine Science Cooperation Program, WHOI, map.
103	Naval Oceanographic Office. (various dates). World Relief Map. Sheets NA6, NA9&9A, NP6, NP9, NP12, NP13.
104	(see Factor 103)
105	(see Factor 103)
106	(see Factor 103)
107	(see Factor 103)
108	(see Factor 103)
109	(see Factor 103)
110	(see Factor 103)
111	(see Factor 103)
201	Vogt, P. R. 1994. DBDB5 analysis.
202	Vogt, P. R. 1994. DBDB5 analysis.
203	Vogt, P. R. 1994. DBDB5 analysis.
204	Vogt, P. R. 1994. DBDB5 analysis.
205	Vogt, P. R. 1994. DBDB5 analysis.
206	Vogt, P. R. 1994. DBDB5 analysis.
207	Vogt, P. R. 1994. DBDB5 analysis.
208	Vogt, P. R. 1994. DBDB5 analysis.
209	Vogt, P. R. 1994. DBDB5 analysis.

distance from the east, west, and gulf coasts of the United States; avoidance of foreign-claimed waters, economic and fisheries zones; and a water depth of 3000 m or more. The definition factors are all exclusion factors and define the total geographic area available for potential site locations. However, because all active 1° squares in the model are populated with all factors, any definition factor may be switched off to expose further areas for consideration and analysis.

(1) 1000-Nautical-Mile Limit (Factor 101)

The 1000-nmi limit, as defined above, was measured on PS-1 (1° longitude = 1-in Mercator projection) maps. One degree squares having about 75% or more area beyond 1000 nmi are treated as excluded. The 1000-nmi-limit factor is not required when distance factors are activated because the distance factors become exclusionary when distance from port exceeds 1000 nmi.

(2) No Foreign Economic Zones (Factor 102)

This factor excludes claimed economic zones for Canada, Mexico, Bermuda, Cuba, Bahamas, Haiti, Dominican Republic, Antigua, & Barbuda, and France (St. Martin and Guadeloupe). Foreign economic zones were compiled and plotted on PS-1 maps. A 200-nmi radius from foreign coasts is the basis for this exclusion, unless otherwise defined by various sources. One degree squares having about 75% or more area within foreign-claimed waters are treated as excluded.

(3) Depth over 3000 Meters (Factor 103)

The 3000-m contour from the World Relief Map, PS-1 scale, of the Naval Oceanographic Office, is the source of this factor. One degree squares having about 75% or more area shallower than 3000 m are treated as excluded.

3.3.3.2 Unique Environments Factors

The unique environments factors are all exclusion factors intended to remove from consideration those seafloor areas that have unique biologic, environmental, or economic properties, as well as potential hazards. The common denominator for these factors is seafloor morphology, which either determines or reflects the biologic, tectonic, and stratigraphic conditions associated with them. Eight areas of unique environments are entered into the model: the Bahama Platform, the Puerto Rico Trench, the Florida Escarpment, the Campeche Escarpment, the Gulf of Mexico Salt Structures, the East Pacific Rise, the Mendocino Fracture Zone, and the Gorda and Juan de Fuca Ridges. The selection of these areas is not intended to be exhaustive, but rather identifies those areas that are significant on the scale of 1° squares. Smaller unique environments are better treated at the first level of a regional site survey.

(1) Bahama Platform (Factor 104)

The Bahama Platform consists of a shallow-water carbonate platform and associated pedestals bounded by steep escarpments that rise from abyssal depths. The carbonate reef

and related communities, located at or near the sea surface, are thus in close lateral proximity to the abyssal seafloor, and may make the area unsuitable for isolation operations.

(2) Puerto Rico Trench (Factor 105)

Although the 8000-m depth of the Puerto Rico Trench might suggest a good isolation site, it is populated by a unique abyssal community that would be adversely affected by a large-scale isolation operation.

(3) Florida Escarpment (Factor 106)

The Florida Escarpment, in the Gulf of Mexico, is a steep incline with exposed carbonate rocks that separates the Florida continental shelf from the Mississippi submarine fan at 3000-m depths. Brine seeps with chemosynthetic communities are present near the base of the escarpment. The escarpment is an unusual geologic and biologic environment, as well as the Marine Sanctuary around the Florida Keys, and should be avoided.

(4) Campeche Escarpment (Factor 107)

The Campeche Escarpment in the Gulf of Mexico is, like the Florida Escarpment, a steep incline with exposed carbonate rocks that separates the reef-bearing Yucatan continental shelf from the abyssal Gulf of Mexico, and should be avoided because of potentially unique communities and its unusual geologic environment.

(5) Salt Structures (Factor 108)

Large portions of the Gulf of Mexico are underlain by a geologically mobilized layer of Jurassic salt. Where it has mobilized, the salt has migrated into domes, diapirs, pillows, and other structures that have penetrated overlying strata and in places on the seafloor. The salt structures have caused large-scale petroleum migration and accumulation, and have long been the focus of major active and projected petroleum production and exploration activities. Although the most evident salt structures are in the northern Gulf, at depths less than 3000 m, significant portions of the abyssal Gulf, the Sigsbee Hills and the northeastern Mississippi Cone, are underlain by salt structures. The combination of potential petroleum resource, geohazards from tectonic movements, brine and petroleum seeps, and the presence of chemosynthetic communities, make the salt structure areas undesirable for waste isolation.

(6) East Pacific Rise (Factor 109)

The East Pacific Rise, located off western Mexico, is an active seafloor-spreading ridge. It is characterized by frequent earthquakes, submarine volcanism, hydrothermal metalliferous brine vents, chemosynthetic vent communities, and thin or absent sediment cover. These conditions make the East Pacific Rise undesirable for large-scale isolation.

(7) Mendocino Fracture Zone (Factor 110)

The Mendocino Fracture Zone, expressed as a large east-west trending topographic offset extending westward from Cape Mendocino, CA, is associated with unusual sediment patterns and significant but poorly understood abyssal circulation. Because of the potential but unclear current effects and related biologic activity, the Mendocino Fracture Zone is best avoided as an isolation site.

(8) Gorda and Juan de Fuca Ridges (Factor 111)

The Gorda and Juan de Fuca Ridges, located off the northwest U.S. and southwest Canada, are active seafloor-spreading ridges. Like the East Pacific Rise, they are characterized by frequent earthquakes, submarine volcanism, hydrothermal metalliferous brine vents, chemosynthetic vent communities, and thin or absent sediment cover. These conditions make the Gorda and Juan de Fuca Ridges undesirable for large-scale isolation.

3.3.3.3 Anthropogenic Factors

Anthropogenic factors that bear directly on site selection are ship traffic and the density of submarine communications cables on the seafloor. Other factors, such as existing waste dumps, shipwrecks, and submarine structures, are essentially point characteristics that do not lend well to areal mapping on a 1° square density, and are better treated in the first-level, regional site survey.

(1) Ship Traffic (Factor 1)

Ship traffic is represented as the annual average instantaneous number of ships present in a 1° square, derived from the Navy Standard Historical Temporal Shipping Database (HITS). Although not an ideal measure of ship density, major shipping lanes and areas of traffic are adequately represented. Limitations are lack of fishing boat data, and the reliance of the database on courses reported prior to sailing, rather than on actual courses.

(2) Submarine Communications Cables (Factor 14)

Submarine communications cables are represented as number of cables per 1° square. The compilation for this factor concentrated principally on active and some recently deactivated cables belonging to the major international cable companies. Thus this factor does not represent all cables present, but those that are of contemporary significance. As cables are laid, activated, deactivated, and retrieved on a continuing basis, an absolute cable density will be difficult to establish.

3.3.3.4 Geologic Factors

Geologic factors judged significant to site selection are seafloor slope, seafloor relief or roughness, sediment accumulation rate, presence of ferromanganese nodules, sediment provinces, and earthquake abundance. Numerous additional geological/geophysical factors could be employed, e.g., depth, sediment thickness, presence of clathrates, geophysical survey density, but were not compiled at this time due to task constraints and their possibly lesser effects on site selection.

(1) Seafloor Slope (Factor 2)

The seafloor slope measure employed here is extracted from the Digital Bathymetric Database, 5 Minute, of the Naval Oceanographic Office (DBDB5). The measure is the maximum slope angle among the 144 $5' \times 5'$ subsquares containing sea data within each 1° square. This measure, essentially the average maximum slope over an approximate 5-nmi

distance, thus is an indicator of the magnitude of the slopes to be found within each 1° square.

(2) Seafloor Roughness (Factor 10)

The seafloor roughness measure employed here is also extracted from DBDB5. The measure is the standard deviation in meters of the sea data in the 144 $5' \times 5'$ DBDB5 subsquares. With this measure, a high standard deviation, corresponding to large variability in depth within the 1° square, is taken to correspond to a high degree of roughness. The roughness and slope measures are interrelated, with the roughness measure expressing seafloor irregularity in depth, and the slope measure indicating maximum seafloor inclination.

(3) Sediment Accumulation Rate (Factor 6)

Sediment accumulation rate is derived from a $2° \times 2°$ database. For the Gulf of Mexico, sediment accumulation rate is derived from the depth-dependent regression equation:

$$Acc = (231)10^{-0.64Z},$$

where Acc is in g/cm^{2}10^{3}yr, and Z is depth in kilometers. The depth used is mean 1° square depth, derived from DBDB5. The data for this factor are generalized and approximate. This factor, although classed as geologic, has perhaps greater biologic significance for site selection. The generally very low sedimentation rates encountered in abyssal areas would have minor effects bearing on site selection, but a much greater effect on benthic communities and productivity.

(4) Ferromanganese Nodules (Factor 11)

Ferromanganese nodules and crusts are entered as present or absent. Numerous data sources and disparities in the presentation of nodule density and quality put a value-based compilation beyond the scope of this task. No ferromanganese nodule fields occur in the Gulf of Mexico.

(5) Sediment Provinces (Factor 12)

Sediment provinces are entered as the predominant seafloor sediment type. Because researchers have used differing sediment classifications the three areas, each area is given its own set of sediment-province factor categories, for a total of 19 categories. Sediment type, as a site selection factor, is an indicator of sediment physical properties, and also an indirect gauge of erosive behavior, the bottom current regime, and of benthic biologic properties.

(6) Earthquake Abundance (Factor 13)

Abundant earthquakes are entered as present for those regions that have two to three or more historically-recorded earthquake epicenters per 1°-square area. Abundant earthquakes affect only the eastern North Pacific, specifically the North American Continental Margin, the East Pacific Rise, and the Gorda and Juan de Fuca Ridges.

3.3.3.5 Biologic Factors

Biologic factors are critical to site selection because of the effect of waste materials on benthic communities, and the uptake and dispersal of waste materials by benthic organisms. Factors considered as measures of abundance and activity of benthic organisms are benthic oxygen flux, sediment organic carbon content, organic carbon burial rate, and benthic biomass, as well as the geologic factor, sediment accumulation rate. These factors are all somewhat interrelated measures of biologic activity. Because measurements and observations at abyssal depths are relatively few, all factors should be used together to provide the best grounded measure of biologic activity. We note that greater detail could be provided for final evaluation of potential dump sites if the resident specific taxa were listed, and if we knew their size distribution, feeding types, rates and modes of reproduction, prey and predators, and growth rates. A goal of site assessment studies should be collecting a relatively complete set of information about the resident taxa prior to dumping. A goal of monitoring would be to assess, in space and time, how these taxa and the natural history of each changes over the course of dumping activities. Ultimately, predictive modeling will require information of this level to successfully include biological processes.

(1) Benthic Oxygen Flux (Factor 3)

Benthic oxygen flux is derived from a 2° × 2° database. For the Gulf of Mexico, benthic oxygen flux is derived from the depth-dependent regression equation:

$$F = (0.167)\ CB^{0.505Z},$$

where F is in mol/m^{2}yr, CB is the organic carbon burial rate, and Z is depth in kilometers. The data for this factor are generalized and approximate.

(2) Sediment Organic Carbon Content (Factor 4)

Sediment organic carbon content for the seafloor surface is derived from a 2° × 2° database. For the Gulf of Mexico, sediment organic carbon content is derived from the depth-dependent regression equation:

$$C = (1.36)10^{-0.06Z},$$

where C is weight percent surface organic carbon and Z is depth in kilometers. The depth used is mean 1°-square depth, derived from DBDB5. The data for this factor are generalized and approximate.

(3) Organic Carbon Burial Rate (Factor 5)

The organic carbon burial rate is derived from a 2° × 2° database. For the Gulf of Mexico, the organic carbon burial rate is derived from the depth-dependent regression equation:

$$CB = (31.4)10^{-0.7Z},$$

where CB is organic carbon burial rate and Z is depth in kilometers. The depth used is mean 1°-square depth, derived from DBDB5. The data for this factor are generalized and approximate.

(4) Benthic Biomass (Factor 19)

Benthic macrofaunal biomass is derived from depth-dependent regression equations. Separate equations were derived for the western North Atlantic (WNA), the Gulf of Mexico (GOM), and for the eastern North Pacific (ENP):

$$BB_{\text{(WNA)}} = (2692)10^{-0.49Z}$$

$$BB_{\text{(GOM)}} = (69.18)10^{-0.43Z}$$

$$BB_{\text{(ENP)}} = (2344)10^{-0.26Z},$$

where *BB* is benthic biomass and *Z* is depth in kilometers. The depth used is mean 1°-square depth, derived from DBDB5. The data for these regressions are sparse and the results are a generalized approximation.

3.3.3.6 Weather Factors

Weather factors are principally of operational interest in the selection of bottom sites, and address the issue of site accessibility. Tropical cyclone frequency, acceptable wave-height frequency, and nonoperational wave-height frequency are the factors currently entered as weather criteria. Additional factors could be employed, such as storm tracks or frequencies, sea-state properties, and ship drift to improve the quality of this criterion. However, within the constraints of this task, the three factors entered provide a reasonable estimate of weather elements critical to site selection.

(1) Tropical Cyclones (Factor 7)

Tropical cyclones are entered as the number of tropical cyclones occurring per year within a 5° square centered on each 1° square. This factor is a measure of operational and transport disruption due to tropical storms, hurricanes, and cyclones.

(2) Acceptable Wave Heights (Factor 8)

Acceptable wave heights are those at or below which normal operations can be conducted. This factor is entered as frequency of wave heights under 1.5 m (5 ft) during the worst month of the year. The worst month is used as the factor because it represents the worst-case conditions, which are representative of about 4 months of the year in all areas. The worst month may serve as a better indicator of undesirable, operation-limiting conditions than an annual average.

(3) Nonoperational Wave Heights (Factor 9)

Nonoperational wave heights represent storm conditions and are those at which over-the-side operations must typically be suspended. This factor is entered as frequency of wave heights over 3.7 m (12 ft) during the worst month of the year. The worst month is used for the same reason it is applied to the acceptable wave-heights factor.

3.3.3.7 Oceanographic Factors

Oceanographic factors are selected to take into consideration surface, intermediate, and bottom currents from the standpoint of both circulation and of local and temporal variations. The included factors are locations of major currents, eddy density, modeled geostrophic surface currents, bottom current intensity, modeled surface current speed, and modeled bottom current speed.

(1) Locations of Major Currents (Factor 15)

Several major, localized currents have speeds far higher than those found over most of the areas. These are the Loop Current in the Gulf of Mexico and the Florida Current and Gulf Stream in the western North Atlantic. The Loop and Florida Currents are entered in those 1° squares where their center positions are generally found. The Gulf Stream is entered for center position and for extreme positions. These currents are strong enough to potentially affect operations, and to some degree they extend the bottom.

(2) Eddy Density (Factor 16)

Eddy density is a measure of the frequency of large-scale eddies, such as those spun off major currents. Eddies can affect the entire water column and produce strong near-bottom currents. For the western North Atlantic, where Gulf Stream eddies are common and have been observed for many years, eddy density is entered as the number of eddies per 1° square per decade. In the Gulf of Mexico and eastern North Pacific, eddy density is estimated as high, medium, or low, with high values for much of the Gulf of Mexico, and low values for the eastern North Pacific.

(3) Surface Current Speed, Geostrophic Model (Factor 17)

Surface current speed, from a geostrophic current model, is entered for winter, and is based on layer thicknesses of 2000 m for the western North Atlantic, 800 m for the Gulf of Mexico, and 1000 m for the eastern North Pacific.

(4) Bottom Current Intensity (Factor 18)

The quantity of reliable, long-term current measurements and observations at or within 100 m of the bottom is so small that reasonable areal extrapolation or modeling of bottom currents is not feasible. Nevertheless, areal knowledge of the magnitude and frequency of near-bottom currents and oscillations is critical to site selection. Existing circulation models cannot address the problem because of limitations to their layer approach and the interaction with fine-scale bottom morphology, and they do not always take tidal and eddy-induced currents into account. Because of these limitations, a qualitative estimate is used to assign 1°-square descriptors of low, medium, and high bottom current intensity. The assignment of the descriptors is based on actual measurements, photographic evidence of currents, eddy kinetic energy calculations, and expected topographic acceleration effects. The descriptors corresponding to the intensity levels are semiquantitative, and are intended as initial guideposts of typical conditions.

(5) Surface Current Speed, Layer Model (Factor 20)

Surface current speed is entered as layer 1 of the 6-layer NRL circulation model. The initial thickness of layer 1 is 135 m.

(6) Bottom Current Speed, Layer Model (Factor 21)

Bottom current speed is entered as layer 6 of the 6-layer NRL circulation model. Layer 6 includes all depths from approximately 1000 m to the seafloor (see Section 5.1.2, **Physical Oceanographic Modeling**). The magnitude of layer 6 thickness makes this factor a generalized measure of current speed for the lower water column as well. The layer 6 computed speeds are much lower than measured maximum speeds near the bottom. This factor can be thought of as a measure of transport, and only as a relative first-order measure of the distribution of bottom current speed. It is best used in conjunction with the bottom current intensity factor.

3.3.3.8 Distance Factors for Major Ports (Factors 201–209)

The distance factors are entered as distance from major U.S. ports of egress to the centers of 1° squares via great circle routes. New York, Norfolk, Charleston, and Miami are included for the western North Atlantic; New Orleans and Galveston for the Gulf of Mexico; and Los Angeles, San Francisco, and Seattle for the eastern North Pacific. Distance factors are ocean area specific, and each area must be modeled one at a time to obtain valid scores. Unlike all other factors, distance factors do not represent an intrinsic characteristic of the environment of a 1° square. They are appropriate for logistics scenarios. If used together with environmental factors for site optimization, distance factors must be treated cautiously, particularly when heavily weighted, or they may grossly distort the intended environmental optimization.

3.3.4 Model Scenarios and Results

The Site Selection Model was used to identify optimal locations for abyssal waste isolation in the western North Atlantic, the Gulf of Mexico, and the eastern North Pacific. NRL environmental task participants (F. A. Bowles, P. Fleischer, P. C. Gallacher, M. D. Richardson, and D. K. Young) jointly conducted the factor weighting and scoring after solicited inputs and comments were collected from all relevant project contributors. The weighting and scoring exercise was an iterative process of (a) determining the relative importance of each functional criterion, (b) selecting the applicable factors to be included, (c) assigning factor weightings, (d) assigning category scores to each factor, and (e) identifying exclusionary factors and factor categories. It is important to note here that the scoring and weighting process contains no a priori geographic considerations. It effectively filters out any geographic bias toward specific locations, and treats the three ocean areas equally. The resultant optimal sites and their relative scores represent a documented decision on their comparative suitability for waste isolation.

Two additional site-optimization scenarios were modeled by the environmental task participants. The first is a waste dispersal scenario, in which waste disposal is achieved by optimal dispersion in the water column and on the seafloor. The second is a logistics

scenario, which considers only factors affecting transport and operational conditions. The purpose of presenting these scenarios is to demonstrate the effect of the environment on site location when other disposal schemes are adopted, and to illustrate the adaptability of the model to a variety of site optimization tasks.

Model inputs of factor weightings for the isolation scenario, as well as those for the dispersal and logistics scenarios, are given in Table 3.3.3-1. Factor-category scores for the scenarios are shown in Table 3.3.3-2. Appendix A gives complete model outputs as a tabulation of geographically referenced 1° squares and their scores for each scenario. Table 3.3.4-1 provides model output summary statistics, and Table 3.3.4-2 gives the locations and scores for the 10 1° squares with the highest scores in each ocean area. The rules that were followed for the weighting and scoring in Tables 3.3.4-1 and 3.3.4-2 are listed in Table 3.3.4-3. Figure 3.3.4-1 is a map display of all active 1° squares and locations of the Surrogate Sites. (Surrogate Sites are those sites that were chosen as the "best guesses" of locations for isolation purposes prior to the final site selection process. This was necessitated by the needs of the Engineering and Economics groups for their analytical needs early in the project.) Figure 3.3.4-2 is a map of the definition scenario showing the allowable 1° squares as defined by the project definition factors. The model outputs of 1°-square scores are displayed for each of the three scenarios in a set of four figures each (Figs. 3.3.4-3 through 3.3.4-14): (1) a thematic map of all 1°-square scores, (2) a thematic map of the ten highest-scoring squares in each ocean area by rank, (3) a histogram of scores of 1° squares grouped by area, and (4) a histogram of score frequency of 1° squares for each area. These figures and tables are the basis for the discussion in the following subsections.

3.3.4.1 Isolation Scenario

Identification of optimal sites for isolation of waste on the abyssal seafloor is the focus of this section, and the primary objective of the Site Selection Model. Even though the model produces objective and reproducible results, the selection of environmental factors and determination of relative impact remains a somewhat subjective exercise that must be guided by informed, scientific judgment. Current state of knowledge of important abyssal seafloor processes, particularly for currents and biologic activity, is typically limited to sparse point observations. Extrapolations from these limited data are consequently suspect, and must be performed to obtain an initial understanding of these processes on an areal and regional basis. The application of numerous, often somewhat duplicative, factors in the model is regarded as an asset in that among combinations of low-quality and overlapping factors, certain elements of commonality will cause amplification, and disparities will cancel each other.

(1) Assigned Weights and Scores

For the isolation scenario weighting (Table 3.3.3-1), all definition factors and unique-environments factors are turned on (excluded). Distance factors are not used (weighted 0%). Among the category factors, the oceanographic group, or currents, has the highest weighting, 29%, with 18% on bottom-current measures. Factor 17, surface-current speed, geostrophic model, was not weighted as it is duplicative and of lower quality than factor

Table 3.3.4-1. Site Selection Model: Summary Statistics.

	WNA	GOM	ENP	*ALL*
DEFINITION SCENARIO				
Total No. of 1° Squares	779	160	1302	2241
Excluded squares	428	141	589	1158
Included squares	351	19	713	1083
% excluded	54.9	88.1	45.2	51.7
% included	45.1	11.9	54.8	48.3
ISOLATION SCENARIO				
Excluded squares	500	147	1123	1770
Included squares	279	13	179	471
% excluded	64.2	91.9	86.3	79.0
% included	35.8	8.1	13.7	21.0
Maximum % score	89.25	71.12	84.25	89.25
Minimum % score	33.87	54.50	34.50	33.87
Median % score	63.75	66.00	73.75	66.50
Mean % score	64.33	64.30	70.14	66.54
Std Dev of % score	11.64	5.36	10.33	11.37
DISPERSAL SCENARIO				
Excluded squares	500	147	1123	1770
Included squares	279	13	179	471
% excluded	64.2	91.9	86.3	79.0
% included	35.8	8.1	13.7	21.0
Maximum % score	60.12	48.50	74.75	74.75
Minimum % score	0.00	0.00	0.00	0.00
Median % score	0.00	0.00	0.00	0.00
Mean % score	12.76	3.29	5.71	7.99
Std Dev of % score	17.55	11.16	14.89	16.03
LOGISTICS SCENARIO				
Excluded squares	522	147	983	1652
Included squares	257	13	319	589
% excluded	67.0	91.9	75.5	73.7
% included	33.0	8.1	24.5	26.3
Maximum % score	57.28	63.56	90.06	90.06
Minimum % score	15.04	50.46	25.67	15.04
Median % score	34.55	59.61	49.33	43.87
Mean % score	35.69	58.94	51.00	44.49
Std Dev of % score	10.01	3.47	13.01	14.03

Table 3.3.4-2. Site Selection Model: 1° Squares with Highest Scores. Overall highest scores are highlighted.

Western North Atlantic			Gulf of Mexico			Eastern North Pacific		
% score	latitude	longitude	% score	latitude	longitude	% score	latitude	longitude
ISOLATION SCENARIO								
89.2	**29.5**	**-70.5**	71.1	24.5	-93.5	**84.2**	**29.5**	**-141.5**
89.2	**26.5**	**-70.5**	70.7	24.5	-85.5	83.2	26.5	-129.5
88.5	**27.5**	**-70.5**	68.7	25.5	-90.5	83.2	27.5	-128.5
87.9	**25.5**	**-70.5**	68.7	25.5	-89.5	83.0	26.5	-126.5
87.2	**25.5**	**-71.5**	66.7	25.5	-86.5	82.5	26.5	-139.5
86.0	**28.5**	**-70.5**	66.2	25.5	-93.5	82.5	27.5	-138.5
84.7	**22.5**	**-65.5**	66.0	25.5	-92.5	82.5	27.5	-137.5
84.7	**22.5**	**-64.5**	66.0	25.5	-91.5	82.1	27.5	-129.5
84.0	**23.5**	**-65.5**	60.5	26.5	-89.5	82.1	26.5	-128.5
84.0	**23.5**	**-64.5**	59.7	26.5	-90.5	81.9	29.5	-140.5
						81.9	28.5	-137.5
						81.9	29.5	-137.5

Table 3.3.4-2, continued. Site Selection Model: 1° Squares with Highest Scores. Overall highest scores are highlighted.

Western North Atlantic			Gulf of Mexico			Eastern North Pacific		
% score	latitude	longitude	% score	latitude	longitude	% score	latitude	longitude
DISPERSAL SCENARIO								
60.1	43.5	-56.5	48.5	25.5	-88.5	**74.7**	**36.5**	**-122.5**
57.0	30.5	-76.5	47.7	25.5	-87.5	**74.2**	**34.5**	**-121.5**
56.6	43.5	-54.5	47.0	24.5	-84.5	**72.5**	**37.5**	**-123.5**
55.9	29.5	-76.5	42.7	26.5	-89.5	**68.7**	**36.5**	**-123.5**
55.7	43.5	-55.5	42.0	26.5	-90.5	**65.7**	**33.5**	**-121.5**
55.1	38.5	-70.5	39.2	25.5	-92.5	**65.5**	**36.5**	**-124.5**
54.0	34.5	-73.5	39.2	25.5	-91.5	**64.7**	**32.5**	**-120.5**
53.6	43.5	-57.5	39.0	25.5	-93.5	**63.1**	**35.5**	**-122.5**
52.6	28.5	-76.5	36.5	24.5	-85.5	**62.2**	**32.5**	**-121.5**
51.4	40.5	-52.5	36.5	25.5	-90.5	**61.7**	**39.5**	**-125.5**
			36.5	25.2	-89.5			
LOGISTICS SCENARIO								
57.3	37.5	-72.5	63.6	25.5	-88.5	**90.1**	**31.5**	**-119.5**
56.3	37.5	-71.5	62.1	26.5	-89.5	**83.7**	**31.5**	**-120.5**
54.7	31.5	-75.5	61.6	25.5	-90.5	**83.2**	**32.5**	**-120.5**
54.5	38.5	-70.5	61.6	25.5	-89.5	**81.8**	**33.5**	**-121.5**
54.4	36.5	-72.5	61.1	25.5	-91.5	**81.0**	**32.5**	**-121.5**
54.3	39.5	-68.5	60.2	25.5	-92.5	**79.4**	**31.5**	**-121.5**
53.6	36.5	-71.5	59.6	26.5	-90.5	**79.3**	**33.5**	**-122.5**
52.6	38.5	-69.5	58.8	25.5	-93.5	**78.7**	**32.5**	**-122.5**
52.4	36.5	-70.5	57.6	25.5	-87.5	**77.3**	**31.5**	**-122.5**
52.4	37.5	-70.5	57.2	24.5	-85.5	**77.2**	**30.5**	**-121.5**

Table 3.3.4-3. Factor Weighting and Category-Scoring Rules.

1. The sum of "weight %" must = 100.
2. Under each criterion, "total weight %" is the sum of all included factor weights.
3. Exclusionary factors are "excluded" (factor is activated) or "included" (factor inactive).
4. Excluded factors carry no weight %.
5. To treat a scorable factor as exclusionary, it must be assigned a very low weight % (e.g., 0.001%), a factor-category score of 1 for the included condition, and a large negative score (e. g., -10^7) for the excluded condition.
6. Distance weightings apply individually to each area (WNA, GOM, ENP) and associated ports. Within each area, one or more ports may be weighted, giving a combination score for the squares <1000 nm from all included ports.
7. "Category scores" must be from 1 to 5 (1 is least, 5 is most favorable).
8. Individual factor-categories may be excluded by assigning large negative numbers (e. g.,-1000).

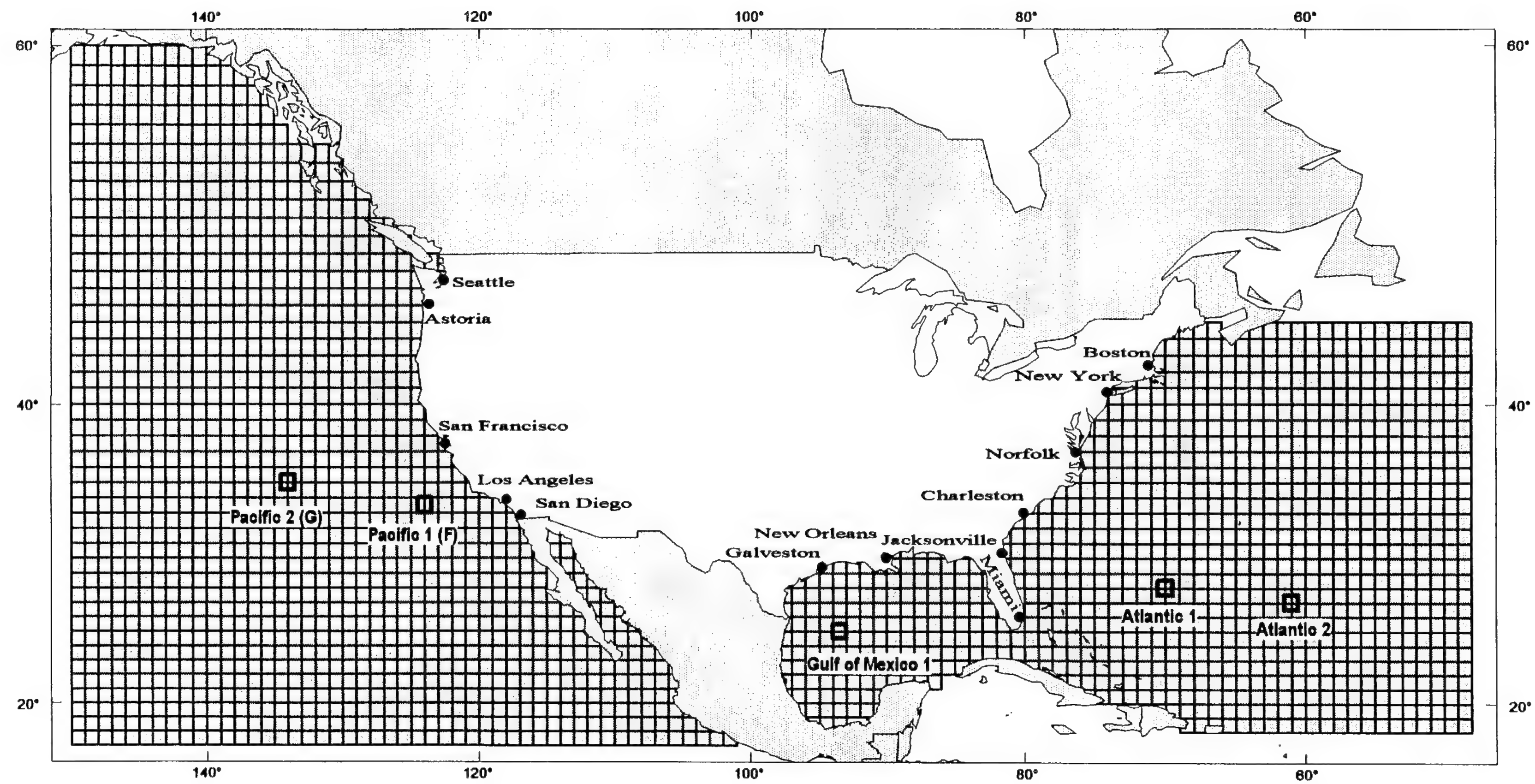


Figure 3.3.4-1. Site Selection Model: Grid of active 1° squares and locations of Surrogate Sites.

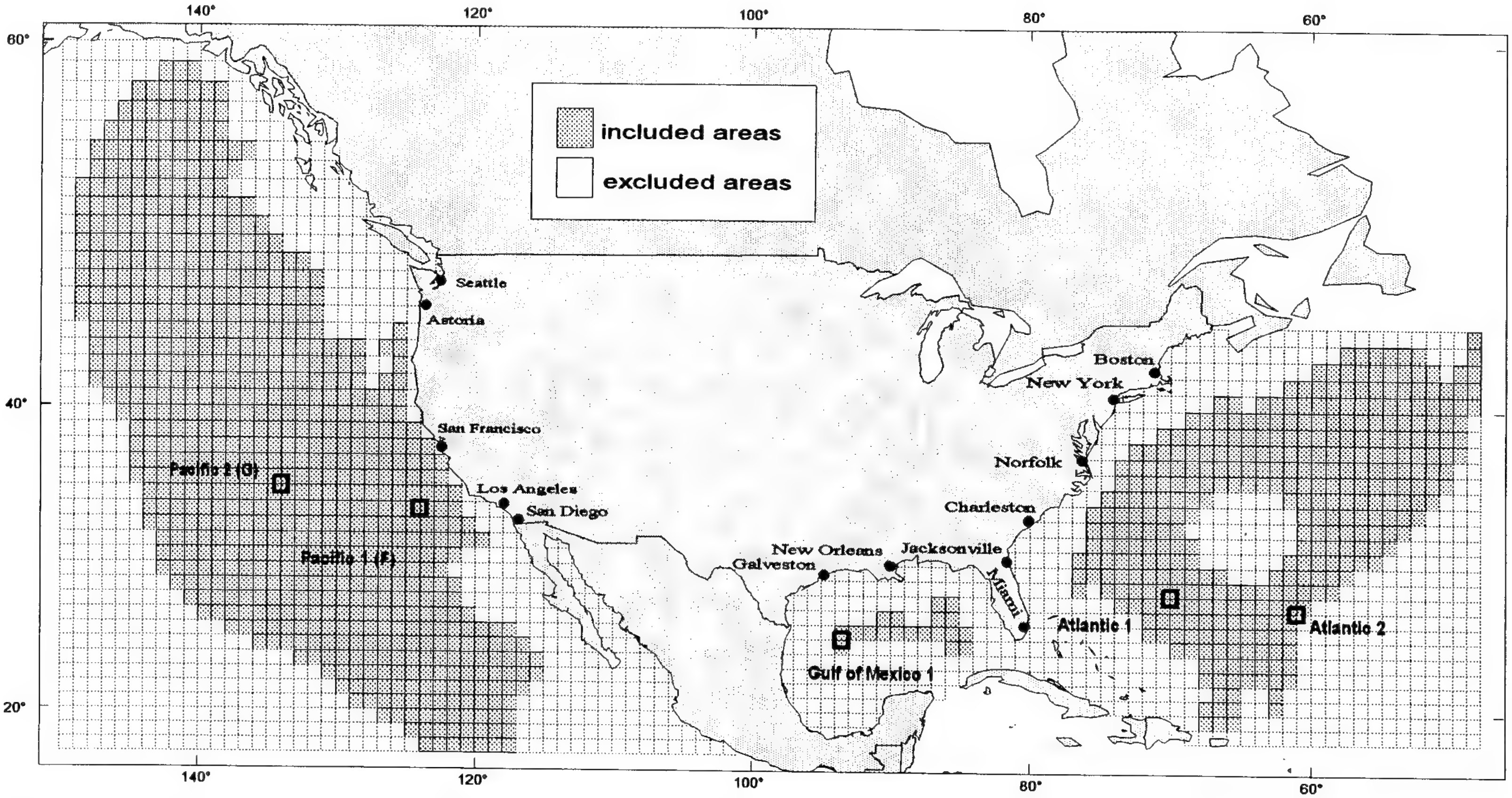


Figure 3.3.4-2. Definition factors for Site Selection Model: 1000 nm distance limit, 3000 m mimimum depth, no foreign EEZs.

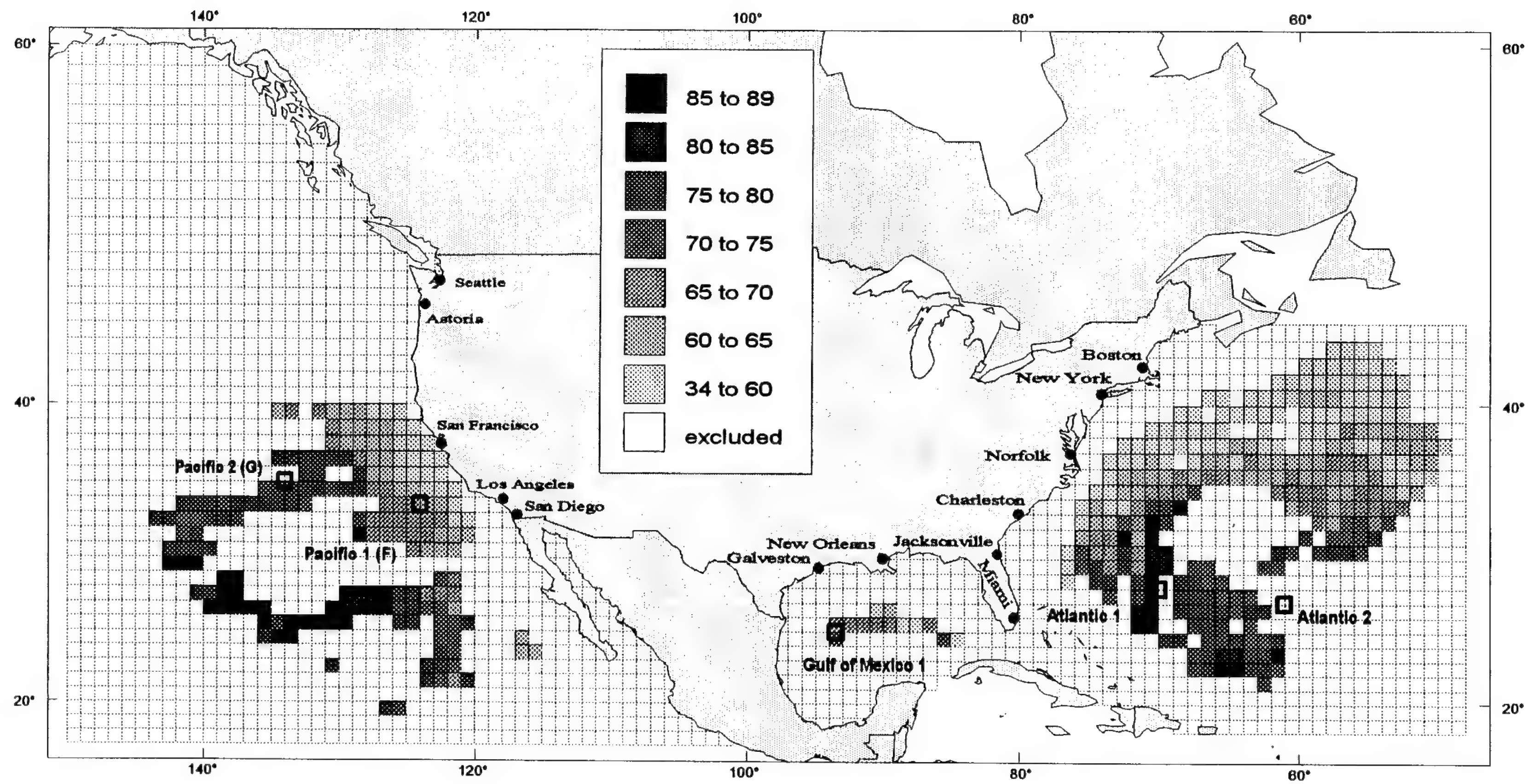


Figure 3.3.4-3. Site Selection Model: Scores for isolation scenario. Scores in percent.

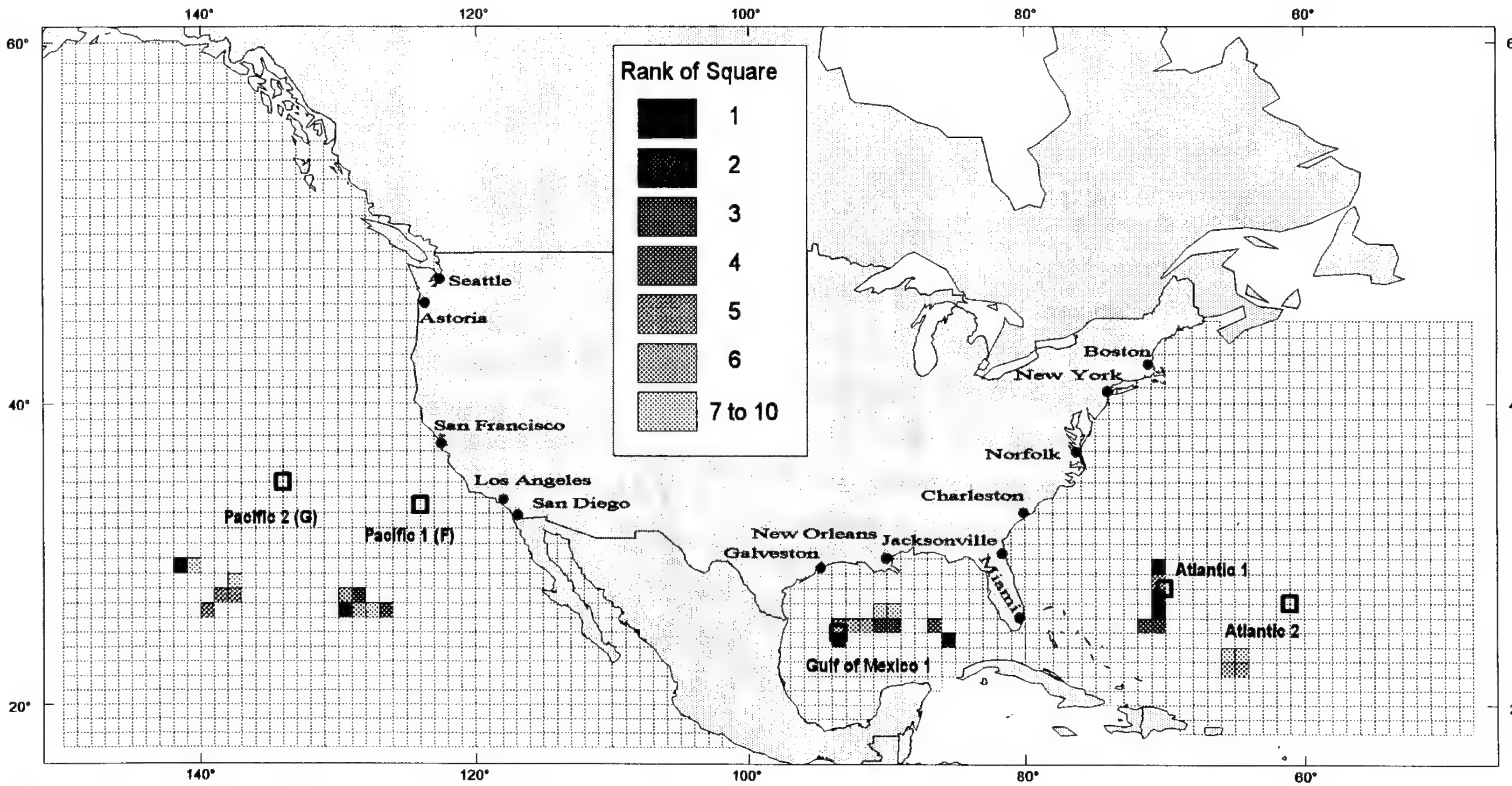


Figure 3.3.4-4. Site Selection Model: Highest-ranking 1° squares for isolation scenario.

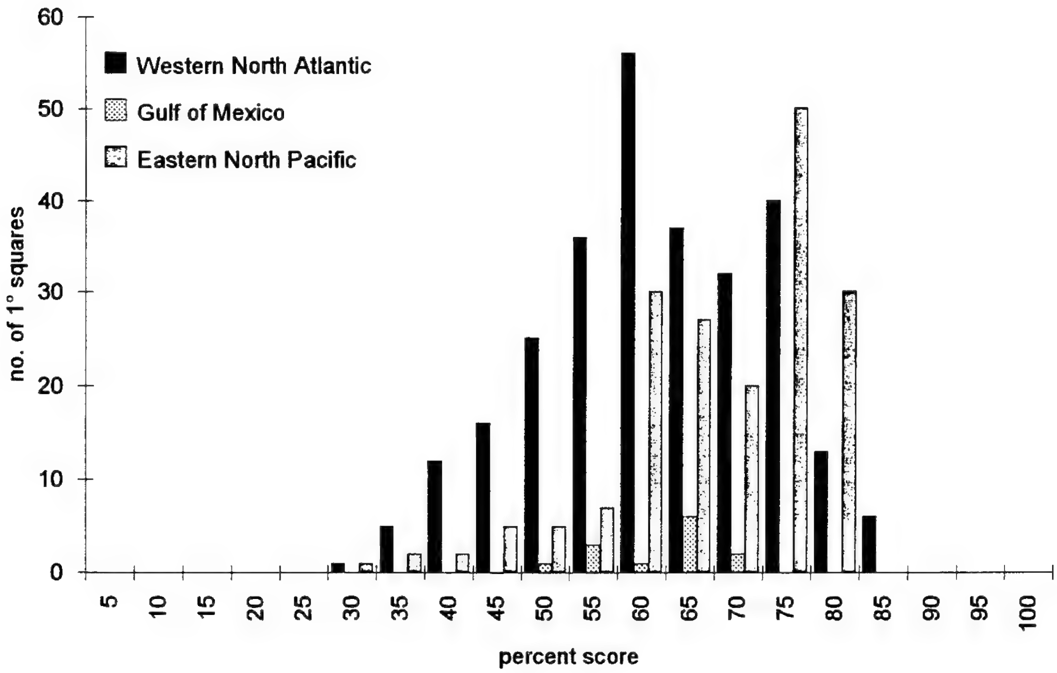


Figure 3.3.4-5. Site Selection Model: Histogram of scores for 1° squares, isolation scenario.

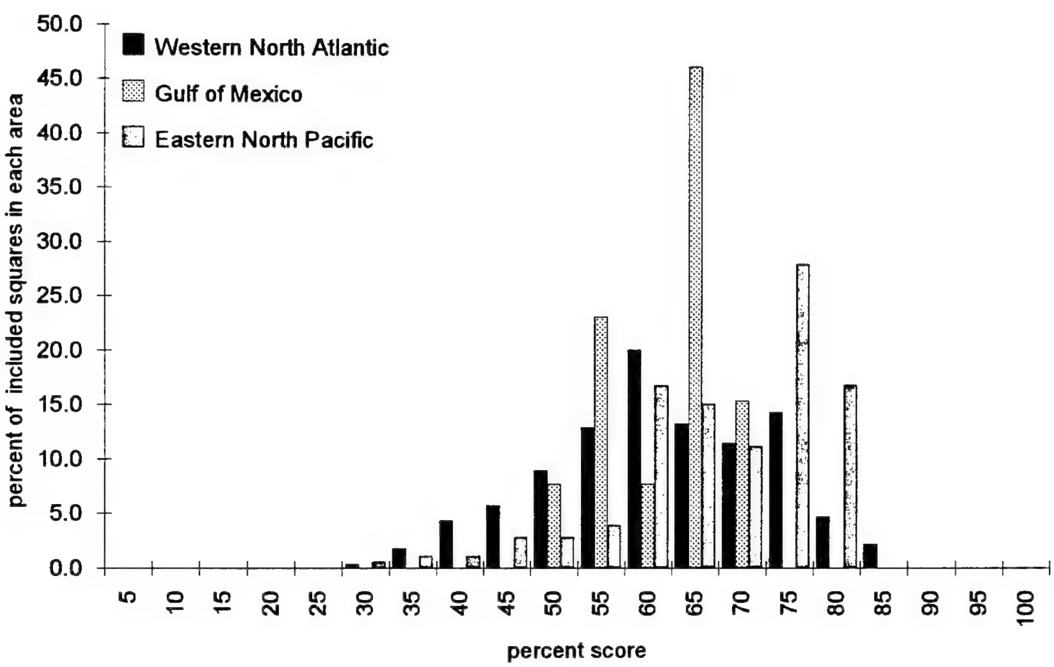


Figure 3.3.4-6. Site Selection Model: Histogram of score frequency, isolation scenario.

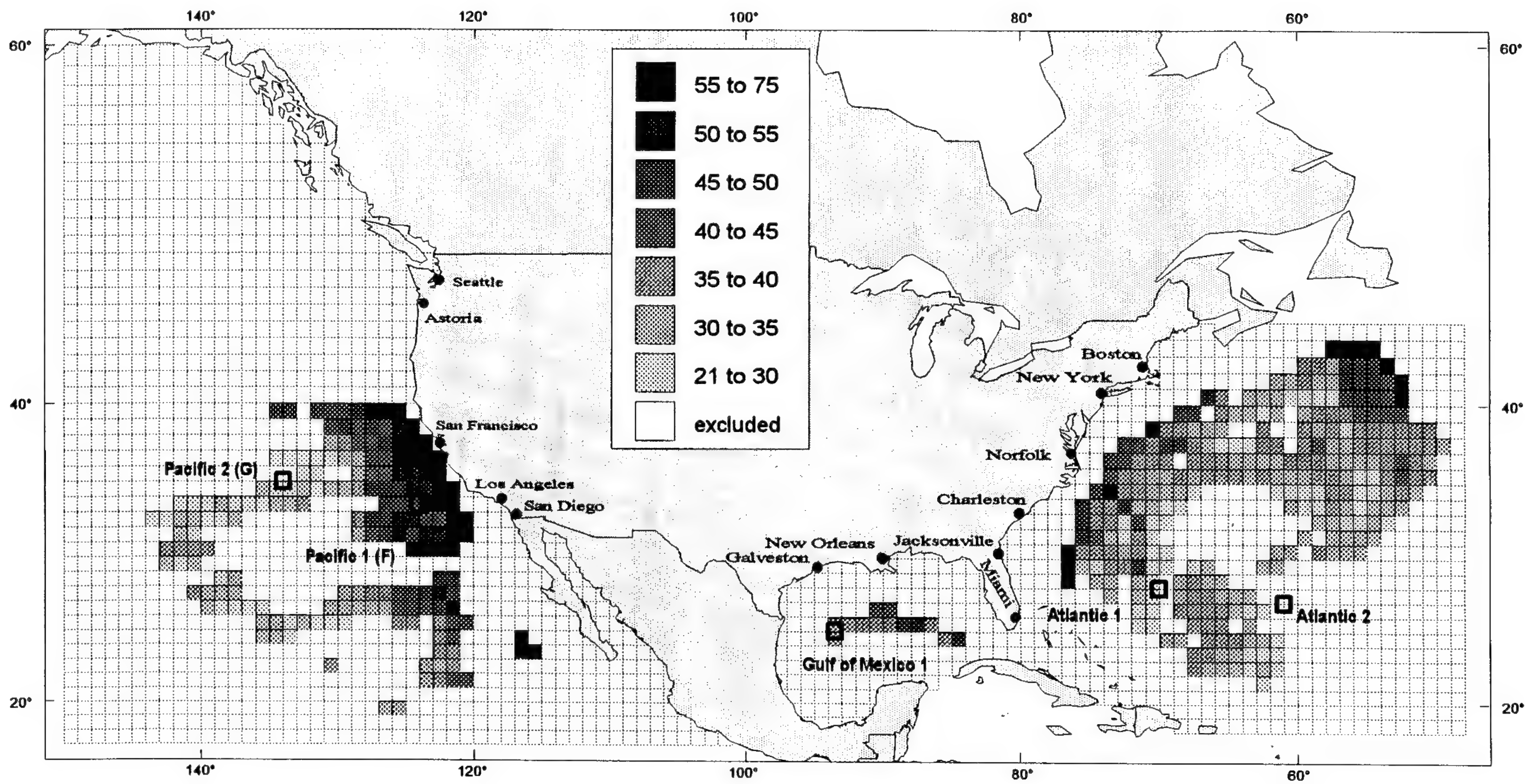


Figure 3.3.4-7. Site Selection Model: Scores for dispersal scenario. Scores in percent.

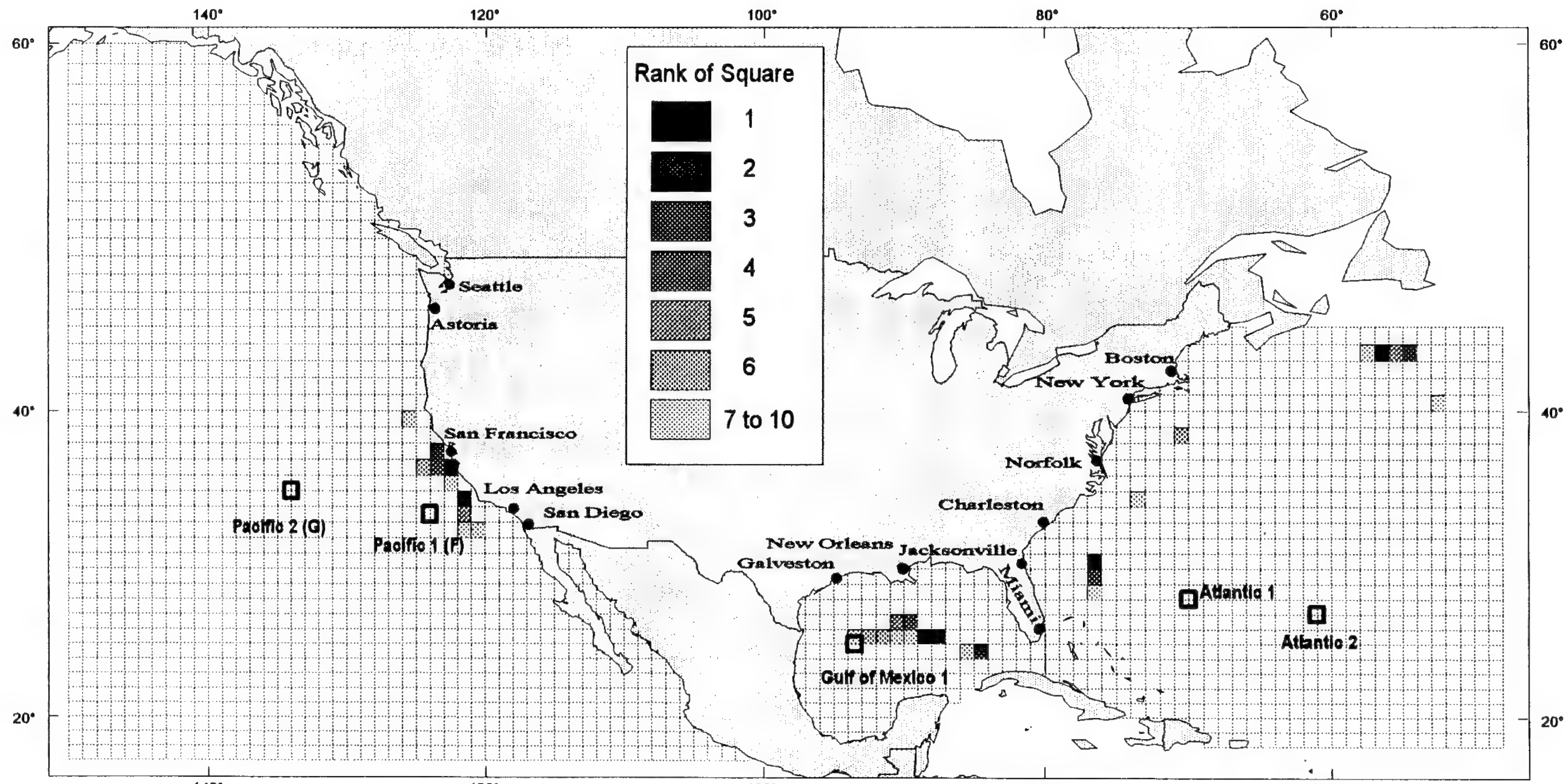


Figure 3.3.4-8. Site Selection Model: Highest-ranking 1° squares for dispersal scenario.

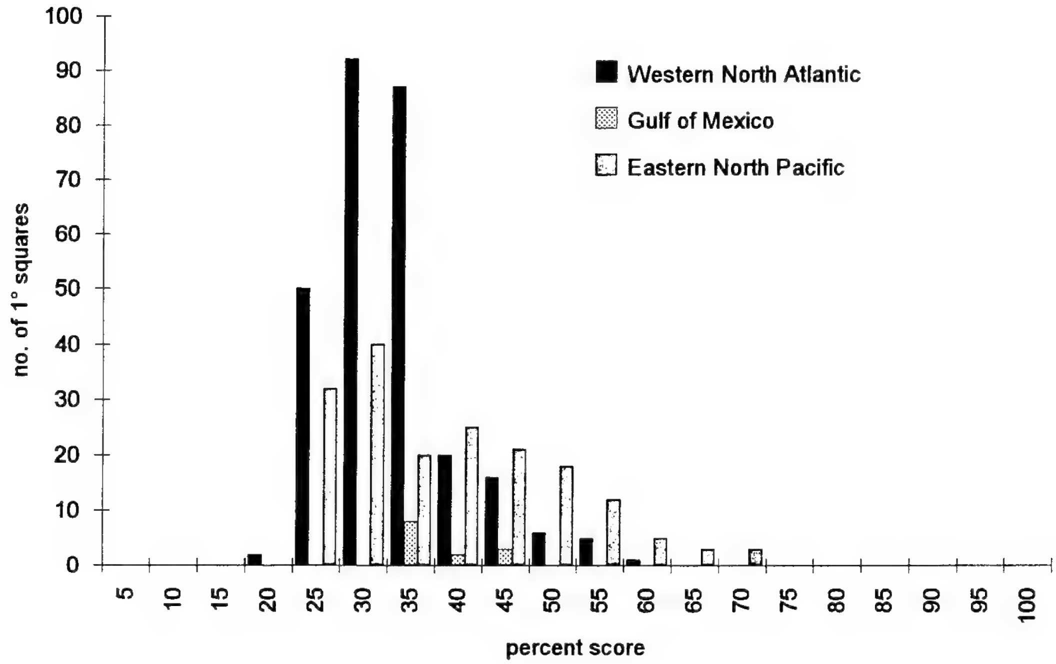


Figure 3.3.4-9. Site Selection Model: Histogram of scores for 1° squares, dispersal scenario.

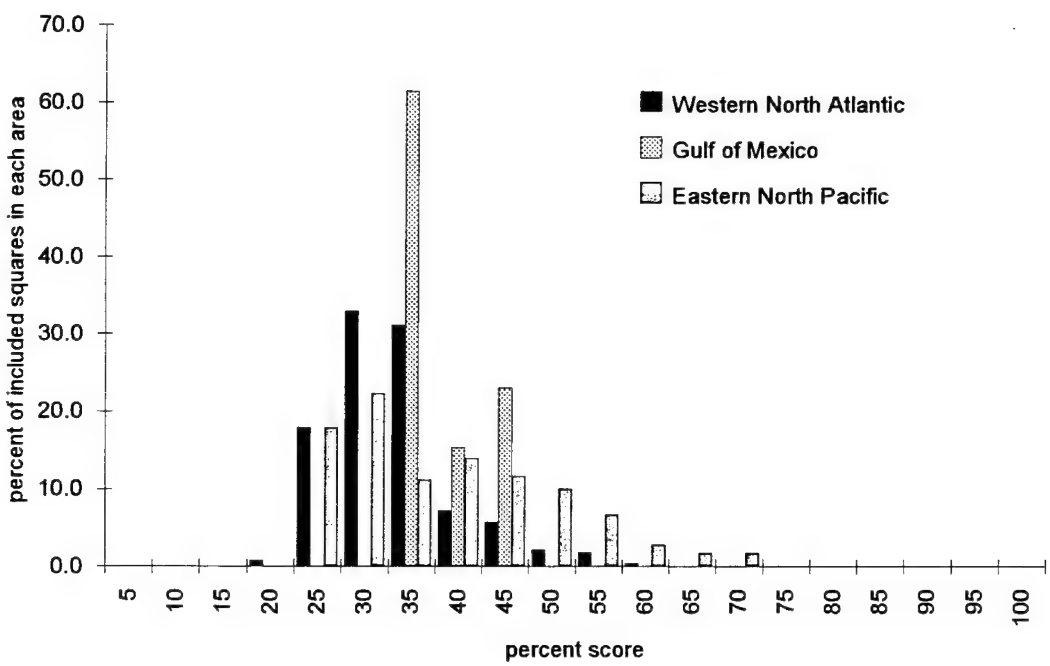


Figure 3.3.4-10. Site Selection Model: Histogram of score frequency, dispersal scenario.

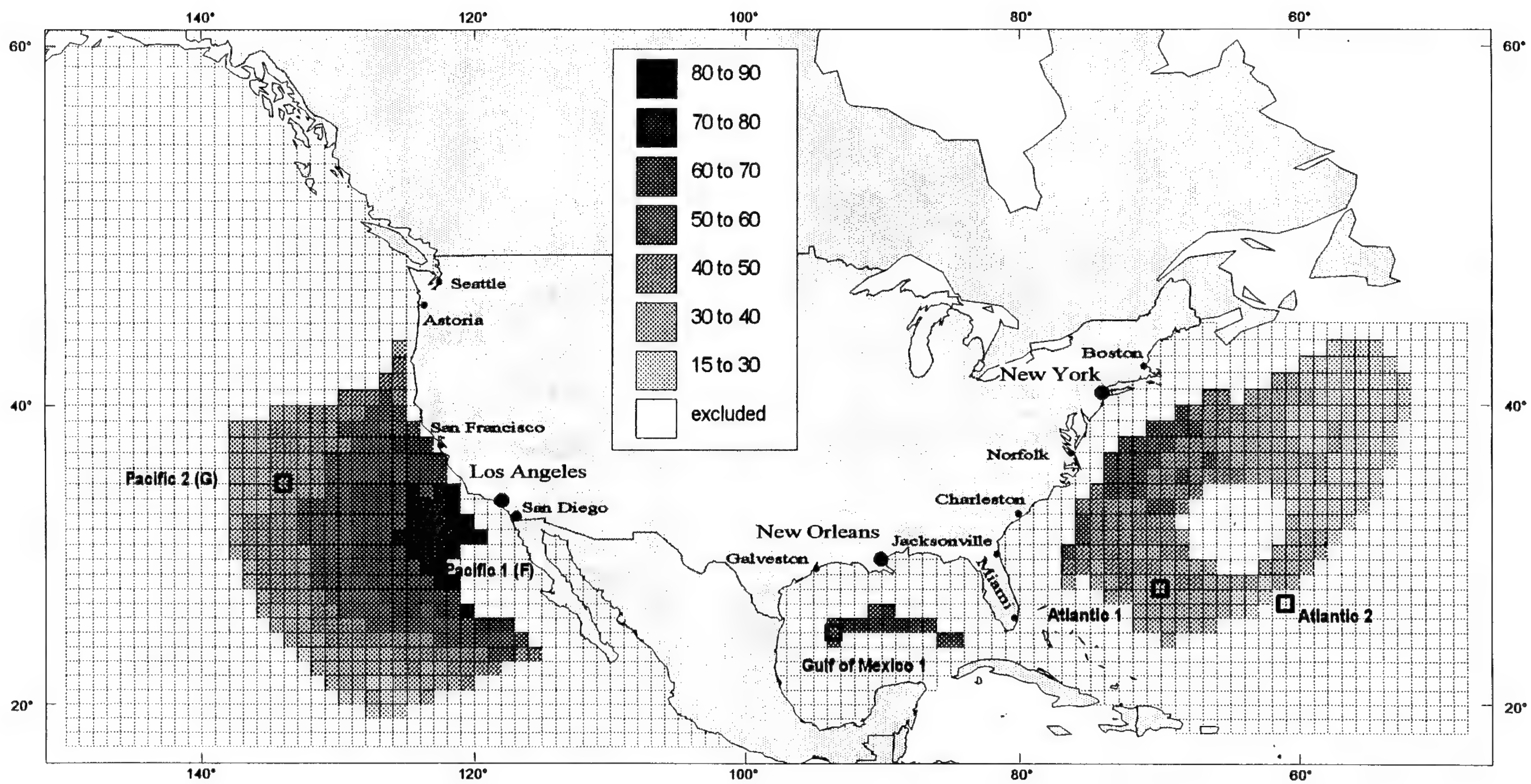


Figure 3.3.4-11. Site Selection Model: Scores for logistics scenario for New York, New Orleans, and Los Angeles. Scores in percent.

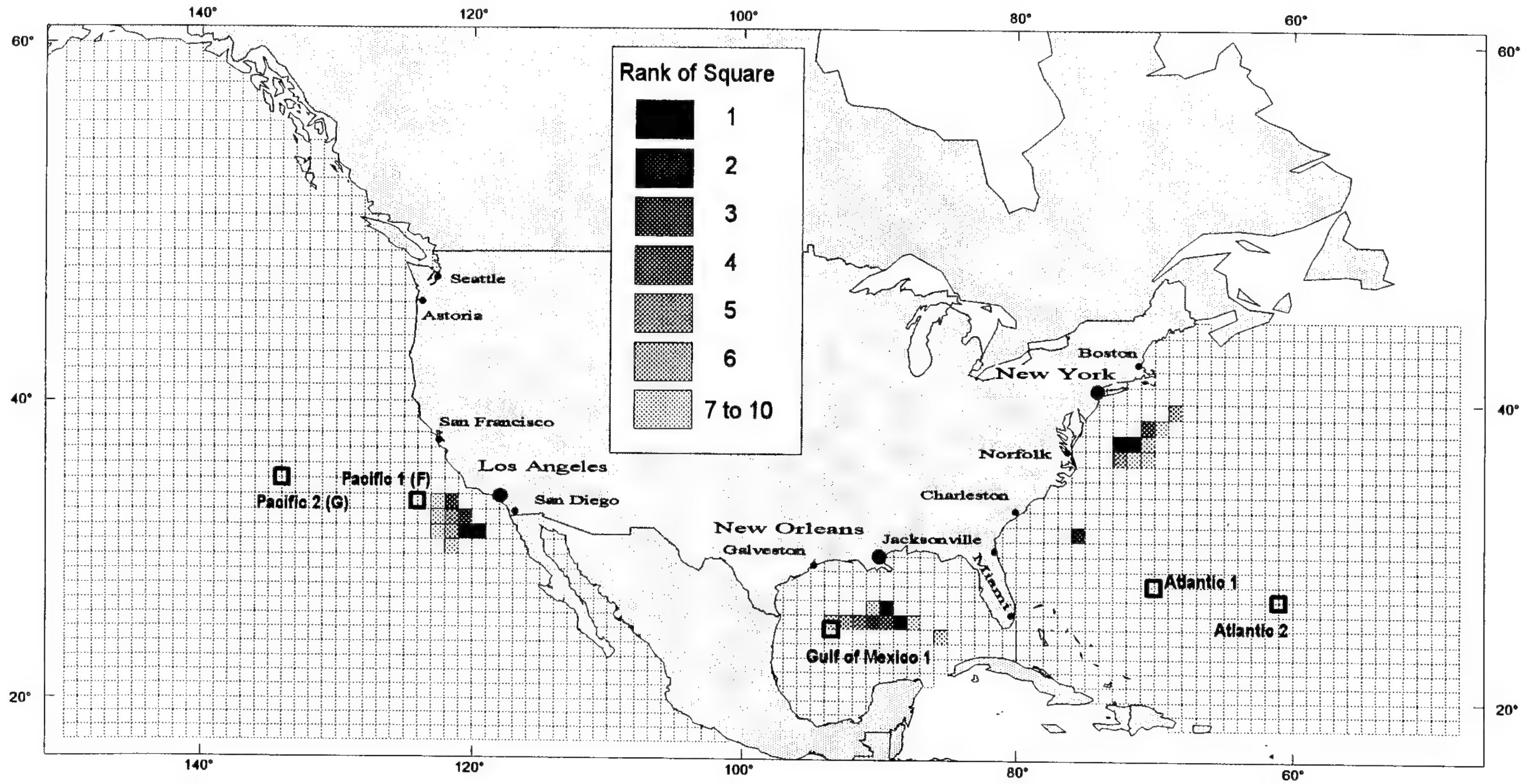


Figure 3.3.4-12. Site Selection Model: Highest-ranking 1° squares, logistics scenario for New York, New Orleans, and Los Angeles.

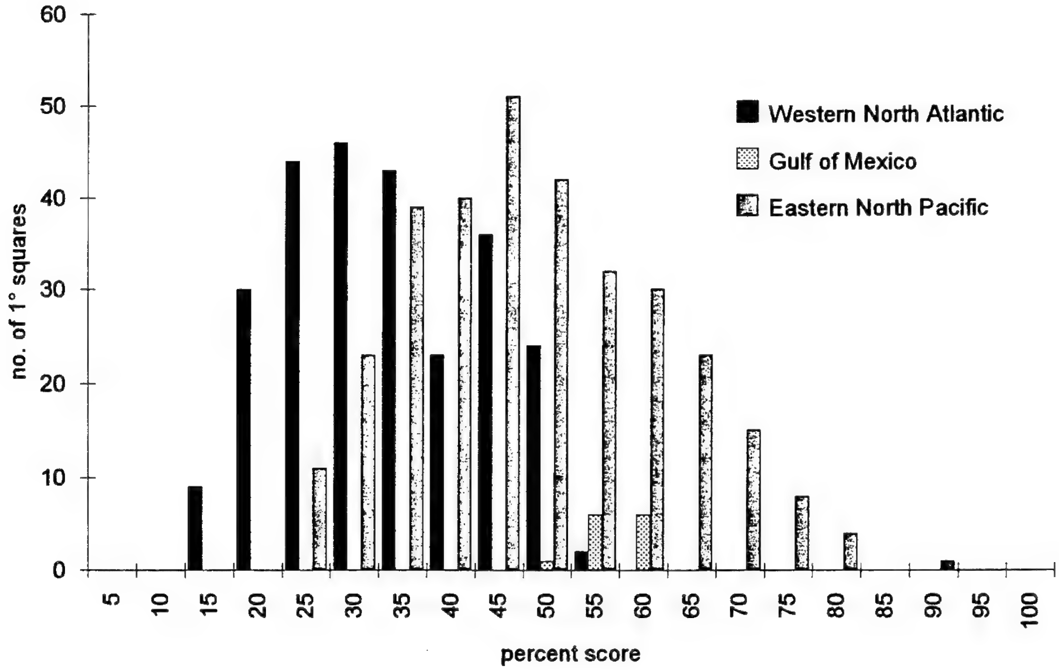


Figure 3.3.4-13. Site Selection Model: Histogram of scores for 1° squares, logistics scenario for New York, New Orleans, and Los Angeles.

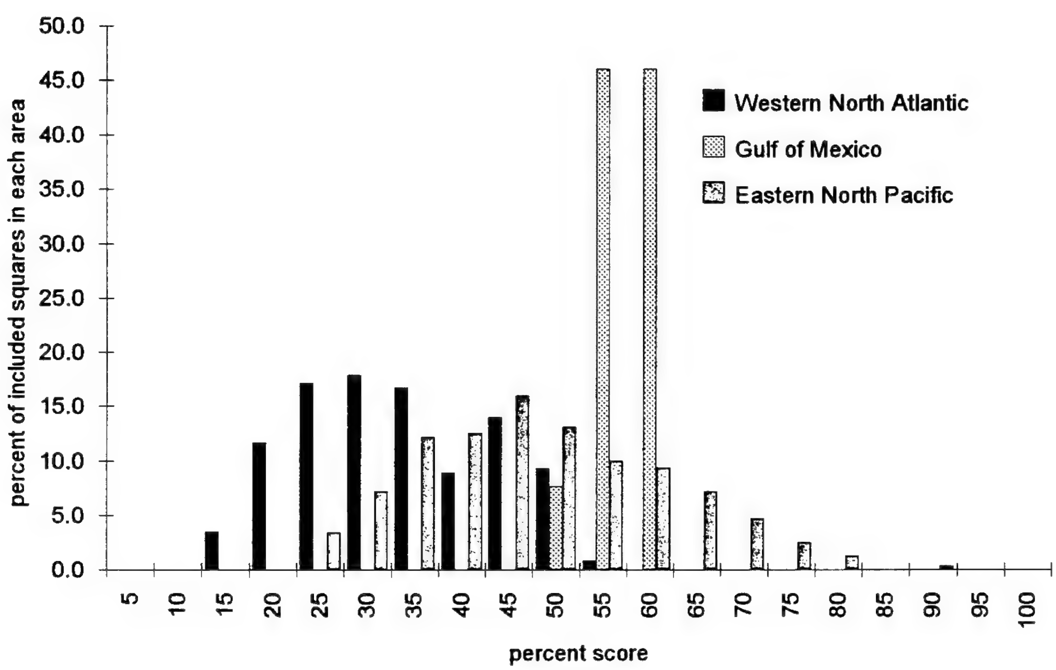


Figure 3.3.4-14. Site Selection Model: Histogram of score frequency, logistics scenario for New York, New Orleans, and Los Angeles.

20, surface-current speed, layer model. The geologic group is weighted 26%. A high weighting of 15% is placed on sediment provinces. Sediment provinces are generally well documented and understood, and they are good general indicators of the seafloor current regime and of biologic activity. The present/absent factors of earthquake abundance and ferromanganese nodules are assigned insignificant weightings because they are treated as exclusionary. The set of interrelated biologic factors is weighted uniformly at 20%. The smaller groups of weather and anthropogenic factors have a combined weight of 25%, with nonoperational wave heights as highest weighted factor, 7%, of these groups.

For the category factors (Table 3.3.3-2), each set of factor categories is scored such that the preferred conditions for waste isolation receive the highest score, grading downward for less desirable conditions, and excluding unacceptable conditions. Oceanographic factors are all scored high for low-current activity. Among the geologic group factors, minimum slope, minimum roughness, and low sediment accumulation rate are scored high. The two dual-category factors of abundant earthquakes and manganese nodules are scored as exclusionary for presence of these conditions. Among the sediment province categories, pelagic and calcareous clays are scored highest, and sands, silts, and rock are scored lowest. Biologic factors are scored high for low activity and low organic content. Weather factors are scored high for favorable conditions. Tropical cyclone frequency of 2 or more, and 12-foot wave-height frequency of 50% or more are scored as exclusionary categories. Low communications-cable densities and low ship densities are scored high. Ship density over 4 ships per 1° square is an exclusionary category.

(2) Results and Discussion

The 1° squares allowed to be considered for waste isolation by the project definition factors are shown in Figure 3.3.4-2. Included are 1083 1° squares, of which approximately two-thirds are in the Pacific, and one-third in the Atlantic (Table 3.3.4-1). Only 19 squares are in the Gulf of Mexico due to the 3000-m depth exclusion in the northern gulf and the Mexican economic zone in the southern Gulf of Mexico.

When all factors are applied to the isolation scenario (Fig. 3.3.4-3, Table 3.3.4-1), the number of allowable 1° squares shrinks to 471, with the majority of squares located in the Atlantic. Nonoperational wave heights exclude the northern Pacific and the northeastern Atlantic. Tropical cyclone frequency excludes the southeastern Pacific. Manganese nodules account for most of the remaining excluded squares in the Atlantic and Pacific. High ship traffic reduces the Gulf of Mexico squares to 13.

Among the allowed squares, the higher scores are in the southern Atlantic and western Pacific (Figs. 3.3.4-3 through 3.3.4-6, Tables 3.3.4-1 and 3.3.4-2). The highest-scoring squares, at 89%, are in the Atlantic, but more high-scoring squares are in the Pacific: 55% of the squares score over 75%, and only 20% of the Atlantic squares score over 75%. Scores in the Gulf of Mexico are lower; the highest score being 71%.

The highest scores in the Atlantic correspond to the Hatteras Abyssal Plain, and the second-highest scores to the Nares Abyssal Plain. These areas score high due to the presence of low slopes and roughness, favorable sediment types, low current activity, favorable weather, and relatively low biologic and anthropogenic activity. By comparison, scores in

the northern Atlantic are quite low. The combination of the presence of the Gulf Stream plus higher bottom current flow, deteriorating weather, high ship traffic and cable density appear to make this region undesirable for waste isolation even on the potentially favorable seafloor environment of the Sohm Abyssal Plain.

Surrogate Site Atlantic-1 is well located on the eastern edge of the Hatteras Abyssal Plain, on the highest-ranking squares in the Atlantic (Tables 3.3.4-2 and 3.3.4-4). The manganese nodule exclusion area to the east suggests that the site should be moved slightly westward, or that the significance of this manganese nodule area needs to be evaluated in any regional survey for this site. The Atlantic-2 Surrogate Site, on the edge of the 1000-nmi limit, is excluded in the isolation scenario by the presence of manganese nodules in the area. Manganese nodule distribution may be somewhat patchy, and the site might not be excluded when data resolutions of greater than 1° are used. If the exclusion factors surrounding the Atlantic-2 Surrogate Site were removed, this site would score about 80%. Atlantic-2 would then lie in the third-highest-scoring region of the Atlantic.

The highest score in the Gulf of Mexico corresponds to the Gulf of Mexico-1 Surrogate Site, located on the northern Sigsbee Abyssal Plain (Fig. 3.3.4-4). The second-highest score is on the southeastern Mississippi Cone. This site appears to be well chosen, although the small number of 1° squares in the gulf does not provide many options. Removal of the Mexican economic zone exclusion exposes additional 1° squares located on the Sigsbee Abyssal Plain. The four best of these squares score between 72% and 78%. Removal of the economic zone exclusion also establishes that the high-scoring square on the eastern Mississippi Cone is a single, one-square maximum, indicating that the Mississippi Cone is a generally less desirable location than the Sigsbee Abyssal Plain.

In the Pacific, the highest scoring 1° squares are found in level, low-relief regions of the pelagic-clay, abyssal hills province in the western region between the Murray and Molokai Fracture Zones. This region scores high due to the presence of favorable sediment types, low current activity, favorable weather, and low biologic and anthropogenic activity. By comparison, the eastern Pacific scores are quite low. The lower scores are due to a combination of higher biologic activity related to upwelling, sediment provinces, and weather.

Pacific-1 Surrogate Site (Table 3.3.4-4) is located in the relatively low-scoring (60%–70%) eastern region. It is located on the distal Monterey Submarine Fan, in an area of turbidite sedimentation and upwelling. Pacific-2 Surrogate Site, located within the pelagic clay, abyssal hills province between the Murray and Mendocino Fracture Zones, achieved the second-highest score among the Surrogate Sites. Minor adjustment of the Pacific Surrogate Site locations would not substantially improve their scores, and only by relocation to the more distant southern area could the highest-ranking 1° squares be occupied.

3.3.4.2 Dispersal Scenario

A scenario that maximizes dispersion of waste is presented here to illustrate how altering the desired site environmental requirements affects site optimization. A dispersion scenario is the opposite of the isolation scenario for numerous factors, and site selection criteria must be weighted and scored to optimize maximum dispersal.

Table 3.3.4-4. Maximum Scores for Surrogate Sites, Isolation Scenario.

Surrogate Site	Maximum Score
Atlantic 1	88.5 %
Atlantic 2	excluded (80 % if included)
Gulf of Mexico	71.1 %
Pacific 1	66.2 %
Pacific 2	77.2 %

(1) Assigned Weights and Scores

For the dispersal scenario weighting (Table 3.3.3-1), all definition factors and unique-environments factors are turned on (excluded). Distance factors are not used (weighted 0%). Among the category factors, the biologic group has the highest weighting, 28%, with factors weighted uniformly. The geologic group is weighted 26%. A high weighting of 15% is placed on sediment provinces. Sediment provinces are generally well documented and understood, and they are good general indicators of the seafloor current regime and of biologic activity. The oceanographic factors are weighted 21%, with the greatest weight, 14%, on bottom current measures. Factor 17, surface current speed, geostrophic model, was not weighted as it is duplicative and of lower quality than factor 20, surface current speed, layer model. The present/absent factors of earthquake abundance and ferromanganese nodules are assigned insignificant weightings because they are treated as exclusionary. The smaller groups of weather and anthropogenic factors have a combined weight of 25%, with nonoperational wave heights as highest-weighted factor, 7%, of these groups.

For the category factors (Table 3.3.3-2), each set of factor categories is scored such that the preferred conditions for waste dispersal receive the highest score, grading downward for less desirable conditions, and excluding unacceptable conditions. Oceanographic factors are all scored high for high current activity. Among the geologic group, maximum slope, maximum roughness, and high sediment accumulation rate are scored high. The two dual-category factors of abundant earthquakes and manganese nodules are scored as exclusionary for presence of these conditions. Among the sediment province categories, pelagic and calcareous clays are scored lowest, and sands, silts, and rock are scored highest. Biologic factors are scored high for high activity and high organic content. Weather factors are scored high for favorable conditions. Tropical cyclone frequency of 2 or more, and 12-ft wave-height frequency of 50% or more are scored as exclusionary categories. Low communications-cable densities and low ship densities are scored high. Ship densities over four ships per 1° square is an exclusionary category.

(2) Results and Discussion

The 1° squares allowed to be considered for dispersal scenario by the project definition factors are shown in Figure 3.3.4-2. They are the same as for the isolation scenario and have the same distribution (Fig. 3.3.4-2, Table 3.3.4-1).

When the all factors are applied to the dispersal scenario (Fig. 3.3.4-7, Table 3.3.4-1), the number of allowable 1° squares again shrinks to 471. The 1°-square distribution is the same as for the isolation scenario because the same excluded factor categories of earthquakes, manganese nodules, high tropical cyclone frequency, high nonoperational wave-height frequency, and high ship traffic apply.

Among the allowed squares, the highest scores are in the eastern Pacific and in the northeastern and western Atlantic regions (Figs. 3.3.4-7 through 3.3.4-10, Tables 3.3.4-1 and 3.3.4-2). The highest-scoring squares, at 61%–74%, as well as the largest number of high-scoring 1° squares, are in the Pacific where 55% of the Pacific squares score over 75%. By contrast, only 20% of the Atlantic squares score over 75%. Scores in the Gulf of Mexico are considerably lower; the highest score being 48.5%. The Pacific scores being

higher in the dispersal scenario than the Atlantic seems counterintuitive in view of the much more active circulation and bottom-current regime of the Atlantic. However, the inclusion of combined weightings of the biologic and geologic factors drive this scenario as it is defined here.

3.3.4.3 Logistics Scenario

A logistics scenario was constructed to demonstrate the effect on site desirability with respect to transport and at-sea operations. Site optimization for logistics is driven by both economic and environmental considerations. In this scenario, New York, New Orleans, and Los Angeles are chosen as ports of egress to the three respective ocean areas. This scenario is intended as an example, and will vary greatly depending on the ports of egress and the distance weighting.

(1) Assigned Weights and Scores

For the transport scenario weighting (Table 3.3.3-1), distance factors are weighted at 50%. All definition factors except the 1000-nmi limit are turned on. The 1000-nmi limit is not needed because the distance factors have their own 1000-nmi limits. The unique-environments factors are turned off (included). Among the category factors, only ship density and weather factors are used. Weather is weighted 40%, equally divided between wave conditions and tropical cyclone frequency, and ship density is weighted 10%.

The relevant category factors (Table 3.3.3-2) are scored such that the preferred conditions for transport and at-sea operation receive the highest score. Weather factors are scored high for favorable conditions. Tropical cyclone frequency of 2 or more, and 12-ft wave-height frequency of 50% or more, are scored as exclusionary categories. Low ship densities are scored high, and ship densities over four ships per 1° square are excluded.

(2) Results and Discussion

The allowable 1° squares for the logistics scenario, defined by the project definition factors with respect to the ports of egress, and by the factor category exclusions, are 589, of which approximately 54% are in the Pacific and 44% in the Atlantic (Fig. 3.3.4-11, Table 3.3.4-1). Again, only 13 squares are in the Gulf of Mexico due to the 3000-m exclusion in the northern gulf, and the Mexican economic zone in the southern Gulf of Mexico. Nonoperational wave heights exclude the northern Pacific and the northwestern Atlantic. Tropical cyclone frequency excludes the southeastern Pacific. Ship traffic removes six squares in the Gulf of Mexico.

The most favorable transport conditions are for the Pacific-Los Angeles scenario (Figs. 3.3.4-11 through 3.3.4-14, Tables 3.3.4-1 and 3.3.4-2), which produces the highest scores and the largest number of high-scoring squares. This result is due to the narrow Pacific continental margin, which makes 3000-m depths more accessible from Los Angeles than those depths from New York, and to the more favorable weather in this part of the Pacific. The Pacific squares score up to 90%, the Gulf of Mexico scores up to 64%, whereas the maximum score in the Atlantic is only 57%.

The relatively smooth, isotropic score pattern for the Pacific-Los Angeles scenario contrasts with the more erratic pattern for the Atlantic-New York scenario. In the case of Los Angeles, weather and ship traffic appear to be minor considerations. For New York, weather and ship traffic can exert a strong influence even with distance weighted 50%.

3.3.5 Conclusions

The Site Selection Model provides a quantitative, reproducible, and documented process to identify optimal sites for the isolation of waste on the abyssal seafloor. By computing normalized, relative scores on a 1°-square basis for all areas under consideration, the model yields an objective geographic measure of suitability within an ocean area, and further allows objective comparisons among areas located in different oceans. Eleven exclusion factors address definitions and unique environments, and 21 scorable factors apply to the biologic, geologic, oceanographic, meteorological, and anthropogenic criteria of potential significance to siting for waste isolation. The entry of factors into the model, and their weighting and scoring, was carefully designed for a waste isolation scenario that emphasizes those attributes having the greatest impact, positive or negative, on potential waste isolation.

The isolation scenario as developed here and applied to the western North Atlantic, Gulf of Mexico, and eastern North Pacific regions reveals that the highest scores, or best locations, for abyssal seafloor waste isolation are in the Atlantic, followed by the Pacific and the Gulf of Mexico. However, the Pacific contains the largest number of high-scoring 1° squares. Within the Atlantic, the best location, as well as the best overall, is on the Hatteras Abyssal Plain. This location corresponds to Atlantic-1 Surrogate Site. The Nares Abyssal Plains is the second-best location in the Atlantic. Atlantic-2 Surrogate Site falls into an exclusion area; without the exclusion, this abyssal hills region would be in the third-best area of the Atlantic. Only 13 1° squares are available for consideration in the Gulf of Mexico as a result of depth and foreign EEZ exclusions. The best location is on the northern Sigsbee Abyssal Plain. The Gulf of Mexico Surrogate Site is also located there. The best locations in the Pacific are in the abyssal hills province of the far southwestern region, between the Murray and Molokai Fracture Zones. Pacific-1 and -2 Surrogate Sites, located closer to ports of egress, are less desirable locations.

The Site Selection Model is the base of a tiered approach in locating a disposal site. The optimum 1° squares identified by the isolation scenario cover large areas of seafloor on which a disposal site might be located. At latitude 30°, a 1° square measures about 111 km by 96 km (60 by 52 nmi, or 69 by 60 statute miles). The actual location of a disposal site will require further, detailed examination of the optimum 1° squares and their surrounding area for existing environmental data, as well as field surveys. This examination corresponds to Tier I of the Survey and Monitoring Plan described in Section 4.0.

The isolation scenario developed here is a robust one. Minor adjustments in weighting and scoring will not appreciably affect the outcome of the scenario. The robustness is due in part to the large number of factors employed, and partly to the overlapping associations among factors as they relate to the criteria, for example sediment type, which, in addition

to having intrinsic significance as a geologic factor, i.e., physical properties, is also an analog for bottom-current energy and for biologic activity.

While the isolation scenario as presently constituted within the Site Selection Model is a reliable and accurate indicator of site desirability, the outcome is a result from an initial version which is subject to improvement by future study. The quality of existing factors can in some cases be improved; for instance, ferromanganese nodule distribution should be quantified by nodule quality, and ship density should include fishing activity. Additional, potentially significant factors may also be added. Examples include current directions, extratropical storm tracks, surface productivity, and whale migration routes. Additional factors may be important for other disposal scenarios.

Selection of factors and definition of scenarios exposes several issues concerning the site selection process. One issue is factor assignments, another issue is data quality.

The selection of appropriate factors, and their relative weighting or importance to a particular scenario, is presently a qualitative and subjective process driven by the pooled scientific knowledge of experts. For instance, we might weight the factor of sediment type heavily because we consider it a high-quality factor that is a good analog for benthic biology and currents, and we assign a certain weight to the lowest layer of the circulation model because it represents our best means of predicting potential dispersal from a source on the abyssal seafloor. These factor selections and weightings are based on our *perception* of their relevance to abyssal seafloor waste isolation, and we have at this point no quantitative, a priori, measures to establish site desirability. Such measures need to be developed. Measures of this type exist to some extent within the regulatory framework for shallow-water and land-based disposal sites. Our present knowledge of the abyssal seafloor, however, is too limited, and our inventory of significant environmental variables too sketchy for us to establish a predetermined, weighted set of attributes to measure site desirability. Additional work, in the form of field observations and experiments, is needed if the factor-selection process for site selection is to be more objective and quantitative.

In the process of factor selection, and in the compiling the database for the Site Selection Model, it became evident that knowledge of certain properties and processes on the abyssal seafloor is sparse. Specifically, there is a lack of (1) congruence for some factors on an inter-ocean basis, and a lack of (2) areally observed or interpolated data for certain critical factors. Lack of uniformity in data description is evidenced by all but the most general abyssal sediment classification schemes, which are often institution- and ocean-basin dependent. Detailed, global descriptions need to be identified or compiled for a number of factors, such as sediment type and ferromanganese nodule characteristics. A more general lack of information on critical factors is exposed by the requirement of the model for factor attributes to be mapped areally with full coverage. The most prominent instance of lack of information, on an areal basis, is for bottom currents. Abyssal bottom-current measurements are few because of sampling difficulties, and extrapolations are problematic due to the complexity and lack of knowledge regarding benthic boundary layer dynamics. Surrogate observations of bottom-current activity, such as from seafloor photographs, are common only in some regions of known high-bottom flow, such as along the western North Atlantic continental margin. Observations such as bottom photographs

integrate the effect of bottom current flow on sediment roughness over periods of years to decades. Time-dependent interactions of currents on the bottom, as well as the importance of rare events (current bursts), is poorly known. Conversely, models of abyssal bottom flow are presently able to reproduce general circulation patterns, but are not capable of predicting flow properties on the seafloor on a regional basis. Measures of biologic factors, such as benthic biomass in abyssal depths, is another area in which knowledge is scant. The depth-dependent regressions employed in the model are based on small numbers of samples, and are essentially first-order measures that need considerable refinement based on more sampling, and probably an inclusion of more variables in addition to depth.

4.0 SITE SURVEY AND MONITORING PLAN *by Frederick A. Bowles and Michael D. Richardson*

4.1 BACKGROUND

Many ocean-disposal sites have received wastes from coastal ports and cities for decades and, as pointed out by Norton (1989), most "were probably originally selected using criteria dominated by navigational and operational considerations with little thought for the potential environmental impact." Today, with the passage of ocean-dumping legislation, predisposal surveys and comprehensive monitoring programs are necessary elements of any proposed disposal of waste, however "benign," on the seafloor. Both elements have been discussed in detail by Bowen and Hollister (1981), but with respect to low-level radioactive waste disposal. Indeed, the disposal of radioactive wastes in the marine environment has concerned scientists, environmentalists, and policymakers for many years (Curtis and Dyer 1993). Research in this area has resulted in an important database for waste-site assessment and site monitoring strategies. Site assessment studies have been conducted off the east and west coasts of the continental United States to address the environmental consequences of deep-ocean disposal of nuclear submarine reactor compartments (Talbert 1982). Even unfortunate events, such as the sinking of nuclear submarines (Sheldon and Michne 1993), offer opportunities to initiate monitoring strategies and evaluate monitoring technology and techniques. In recent years, site characterization studies (biology, geology, sediment geochemistry and geotechnical parameters) have focused on the Madeira and Nares Abyssal Plains (Weaver et al. 1989; Nicholson 1989; Silva et al. 1989; Freeman and Schuttenhelm 1990) as potential radioactive waste disposal sites because they represent remote, deep, tranquil environments.

The prospect of large-scale deep-sea mining operations has resulted in considerable thought about the potential environmental impact. Consideration of baseline environmental conditions and monitoring strategies, as well as sample collection techniques (e.g., hydrographic profiles, sediment cores) and measurements (e.g., nitrate, silicate, turbidity) have been widely addressed. Gerard (1976) has written on potential environmental effects in connection with the recovery of manganese nodules from the ocean floor. Steffin et al. (1979) have focused on the presence and dispersion of the benthic sediment plume resulting from experimental mining operations. Similarly, Yamazake (1990) has addressed the impact of redeposited plume sediments on the benthic community while stressing the need to monitor plumes by means other than passive, moored arrays. In summarizing the MESEDA, DOMES, and DISCOL deep-sea mining studies, Thiel (1991) observes that monitoring of large-scale pilot mining operations is necessary for responsible risk assessment to the environment, i.e., results from small-scale experiments do not extrapolate to full-scale mining operations. In this respect, Gerard (1976) compares the effects of major erosional/depositional process (e.g., turbidity currents, slumps) and large river discharge to the resuspension/deposition of sediment during deep-sea mining operations. Such analogies, he concludes, permit reasonable estimates of anticipated environmental effects resulting from deep-sea mining operations.

The feasibility of deep-ocean disposal of sewage sludge from the U.K. was assessed in comprehensive work by the Institute of Oceanographic Sciences. The work addressed the state of knowledge and the questions that must be addressed if a long-term deep-water sewage sludge dumping program is to be judged environmentally acceptable. Several potential sites in the North Atlantic were examined and near-seabed waste emplacement was recommended rather than release at the ocean surface. The 106-Mile Ocean Disposal Site located in the New York Bight is the only deep-water (2500 m) disposal site in the United States ever designated for dumping of sewage sludge (now closed). As such, it represents a major information source regarding monitoring strategy, sampling design, and predictive modeling (O'Connor et al. 1985; EPA 1989; Menzie et al. 1989; Robertson et al. 1991; Redford et al. 1992; Burch et al. 1993). Initially, it was presumed that dispersal and dilution of sludge in the surface waters would minimize environmental effects. A recent study shows, however, that the waste at the 106-Mile Ocean Disposal Site has reached the seafloor and entered the benthic food web (Van Dover et al. 1992). Emplacement of waste in remote, deep areas of the ocean basin was examined in great detail during a workshop held at Woods Hole Oceanographic Institution (Spencer 1991). Participants addressed the pros and cons of a ten-year-long pilot dumping experiment. Areas considered for the experiment were the Porcupine and Great Meteor Abyssal Plains in the eastern North Atlantic and the southern Hatteras Abyssal Plain in the western North Atlantic. Contained in the report was a scientific plan outlining pre-emplacement site characterization and selection studies and post-emplacement monitoring studies. A long-term "industrial scale" experiment and managed program was thought to provide the best means of assessing the rates of change of the seafloor in response to differing environmental, compositional, and loading factors (Dereck 1991). As before, the extrapolation of small-scale experimental results to larger scales was viewed with skepticism.

It is evident from a perusal of existing literature that site assessment and/or monitoring programs, although directed at different types of waste (e.g., radioactive, sludge, mining, tailings), all employ similar technology and strategies regarding data collection/measurement techniques. Thus, there is general agreement as to what needs to be known about the deep-ocean environment and how to go about acquiring this knowledge before and after waste is placed on the seafloor. Current technology/techniques appear to be adequate for the task (Angel 1990; Chryssostomidis 1991). Nevertheless, it is recognized that there may be a need for new technologies and techniques to meet increasing demands placed on waste disposal site selection and monitoring if dumping ever takes place. Needs for improved existing technology or development of new technology are addressed in an interim report by the Committee on Exclusive Economic Zone Information Needs (Marine Board 1991). More specifically, Thiel et al. (1994) have discussed the scientific requirements for automated, abyssal, benthic laboratories designed to conduct long-term measurements of seafloor processes.

Regarding the risks of deep-ocean waste management, a report by the Marine Policy Center (1993) states that uncertainties arise from a lack of knowledge with respect to: (1) possible irreversible damage to the environment and ecosystem, and (2) net costs. The report suggests that the uncertainties of environmental damage can be resolved by conducting appropriate research. For instance, Barrick and Beller (1989) evaluate two reliability measures (sensitivity and efficiency) as tools for assessing predictions of harmful biological

effects in sediments. Wolfe (1992) has discussed the selection of bioindicators of pollution in relation to a set of monitoring objectives and evaluation criteria. Reducing economic uncertainties, however, may require a deep-ocean disposal experiment of substantial size while "preserving the option of not undertaking full development if the experiment turns out badly" (Marine Policy Center 1993).

4.2 Site Survey Plan

4.2.1 Goal: Isolation

The site survey plan described in the following pages is based on the premise of isolation and containment of waste material in deep-sea locations (greater than 3000 m). The prevalent view (Spencer 1991; Angel 1990; Burnett et al. 1992) is that isolation and containment is preferable to dispersal to spatially restrict the overall impact on the ecosystem, to prevent contamination of the human food chain, and to provide easier and more reliable monitoring of the waste environment. The principal means of minimizing the spread of the waste are by (1) selecting deep-water sites that have low-energy environments; (2) releasing the waste close to the seafloor; and (3) containerizing the waste, such as in bags. In any case, it is accepted that the area of immediate dumping will be profoundly affected, whereas far-field effects are expected to be minimal.

4.2.2 Goal: Identify Baseline

Prior to waste emplacement, it is essential that detailed physical and ecological characteristics of a chosen disposal area be established using state-of-the-art technology. The reason for this is obvious: the main concern with deep-ocean dumping centers around both its impact on the ecosystem and the potential return of contaminants to man. To ascertain this impact, site assessment studies must be conducted to (1) obtain information on processes that are important to understanding the ultimate fates and effects of contaminants and (2) establish geological, chemical, and biological baselines, i.e., the conditions before disposal, that will allow the separation of natural from anthropogenic effects. Natural variability (spatial and temporal) creates a background of change that make it difficult to quantify environmental responses. Thus, defining a meaningful physical or ecological change depends, in part, on identifying and accounting for natural sources of variability. Site characterization, then, involves intensive observation and long-term preemplacement monitoring to determine ambient conditions and the extent of natural fluctuations. In addition, results from site characterization studies validate numerical models that are used to systemize knowledge and predict environmental change.

4.3 Approach to Site Survey

Various site selection criteria are used initially to select favorable regions on the seafloor that would potentially provide for isolation and containment of waste material (see Section3.2, **Mapping**). These regions are then examined in detail for the purpose of

confirming their suitability as disposal sites, choosing the optimal place to put the waste, and establishing the necessary baseline information for subsequent monitoring of the waste distribution as well as the effect of the waste itself on the ecosystem. Because the initial candidate areas are large (5° square), an efficient and feasible methodology is required for identifying and studying the sites. Consequently, a phased strategy has been adopted which systematically focuses on smaller and smaller areas, or tiers, of the seafloor (Fig. 4.3-1).

Phase 1: Represents a regional examination of the seafloor (Tier I) and water column environments based entirely on data found in published literature, databases, and other accessible archives. The key objectives of this initial screening are to (1) select a smaller area (Tier II) of the seafloor within Tier I for more detailed examination and (2) identify deficiencies in the existing database. Included in this phase will be the analysis of model predictions and results based on the utilization of existing data.

Phase 2: Involves major expenditures of field time spent surveying and sampling both the water column and the sediments in Tier II. State-of-the-art techniques are utilized to provide detailed environment characterization and to select subareas within Tier II for more concentrated study.

Phase 3: Focuses on highly detailed site-specific data collection in small (0.1° squares) subareas (Tier III) that have been designated as primary disposal sites based on the evaluation of the data collected during Phase 2. Some regional survey and sampling procedures used in Phase 2 do not need to be repeated. The instruments and techniques used during this phase reflect the requirement for fine-scale coverage of the site-specific disposal areas.

4.4 Measurement and Sampling Program

Detailed regional (Tier II) and site-specific (Tier III) surveys, involving all disciplines of oceanography, should be conducted to quantitatively characterize the seafloor and water column environments under a range of factors relevant to deep-sea waste disposal (e.g., resuspension by currents). Table 4.4-1 summarizes the nature of the field effort required to achieve these goals as defined mainly by four functional areas, i.e., surveys, samples, field measurements, and observations. The separations are arbitrarily made on the basis that (1) surveys involve underway data collection techniques; (2) field samples are usually stored for later processing and analyses in shore-based laboratories; (3) field measurements are, by definition, largely completed in the field; and (4) observations are visual and usually, but not necessarily, qualitative in nature. The last two functional areas, models and databases, are not directly part of the field effort, but nonetheless are important in guiding measurement and sampling programs.

Figure 4.4-1 is a comprehensive breakdown of the sampling and measurement program that one would undertake to fully characterize the ambient physical, chemical, and biological environment before emplacement of waste material. Figure 4.4-1 functions as a flow chart and is intended to show not only the linkage of these techniques but also the volume and scope of information that can be derived, often from a single sample (e.g., a core).

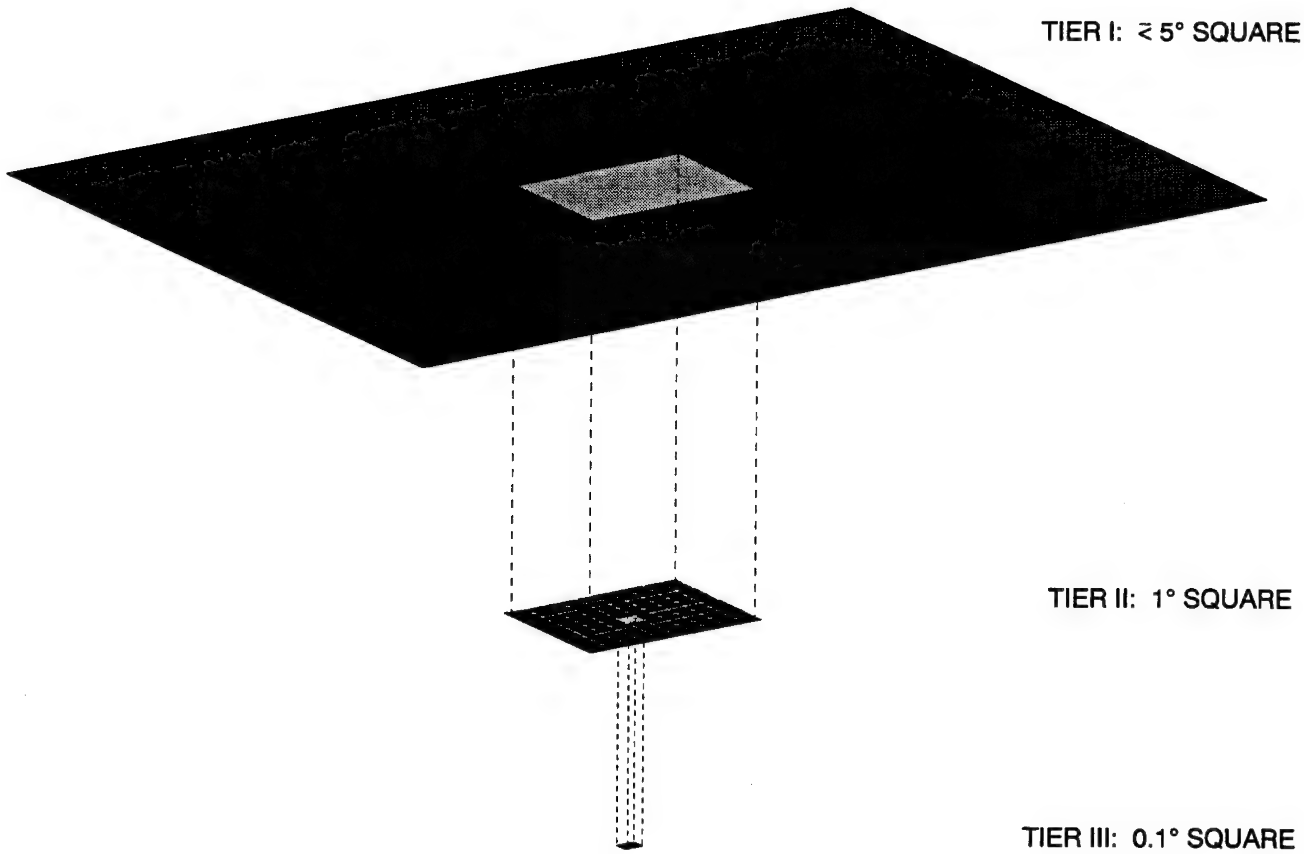


Fig. 4.3-1. Drawing illustrating tiered approach to surveying the sea floor for selection of waste disposal sites.

4.4.1 TIER I

As outlined above, the examination of Tier I requires no field work beyond that which already exists. The primary objectives are to (1) establish, from existing data, what is known in qualitative and quantitative terms about the area and (2) identify a smaller, potentially acceptable waste disposal area (Tier II) to be studied in greater detail. This will involve the evaluation of data from the oceanographic disciplines, marine resources, etc. In addition to specific research papers, archival data will be compiled from academic, private, and government organizations within the United States (e.g., U.S. Navy, NOAA, U.S. Geological Survey, etc.) and possibly foreign institutions.

4.4.2 TIER II

Despite a major downsizing of area (relative to Tier I), the examination of Tier II will entail major field efforts involving detailed survey and sampling schemes. New information and/or more complete data sets will undoubtedly be needed to assess the compatibility of Tier II with deep-ocean waste isolation goals (isolation and containment). In meeting this objective, the data will be used to fully characterize the physical, chemical, and biological environments of both the water column and seafloor and to establish environmental baselines for post-emplacement environmental assessment (i.e., monitoring).

4.4.2.1 Geophysical Measurements

An assortment of geophysical tools will be used to map and characterize the morphology, sediment thickness, and gross sediment textural characteristics of the bottom. The objective is largely twofold (1) to determine the physical processes that control deposition and, particularly, erosion within Tier II and (2) identify the area, or areas, within Tier II that will actually receive waste material.

(1) **Multibeam**: Multibeam systems are designed to provide high-resolution (1-m), accurate (1% of depth), bathymetric (depth) measurements within a strip (swath) of seafloor beneath a ship (Tyce 1986). The bathymetric data is merged (aboard ship) with navigation to create a database from which various map presentations can be produced as such traditional contour maps or 3D projections of the seafloor.

Roughly speaking, a 1° square is about 12,360 km^2 (3600 sq. nmi). Assuming a swath width of about 4 km (2.2 nmi), 25 parallel survey lines, and a speed of about 15 kt, it will take about 4.6 days to achieve 100% bathymetric coverage of Tier II using multibeam instrumentation.

(2) **Sidescan**: Side-looking sonars, or sidescan sonars, are swath mapping systems that produce sonar images of the seafloor, analogous to aerial photographs (taken with the sun at a low angle), except that sonar images record the strength of acoustic signals returned from the seafloor. The images contain information regarding seafloor morphology and roughness that permit geologists to understand tectonic and sedimentary processes.

Table 4.4-1. Integration of site survey/monitoring functions with site survey tiers.

	FUNCTION	TECHNIQUE	PURPOSE	Site Baseline Information			Site Monitoring	
				Tier I	Tier II	Tier III	Tiers II + III	
				1-5° sqr	1° sqr	0.1° sqr	Near Field	Far Field
SURVEYS	Bathymetric	Multibeam (100% coverage)	Detailed Bathymetry/Topography	Regional Compilations Utilizing Published and Archival Data	✓			
	Morphologic	Sidescan (30-200 kHz)	Seafloor Morphology, Bedforms,					
		...Surface-Tow (120% coverage)	Processes, Acoustic Lithology,		✓			
		...Deep-Tow (120% coverage)	Characterize Waste Pile			✓	✗	
	High-Resolution Subbottom Profiles	3.5 kHz/12 kHz	Shallow Subbottom Sediment Structure		✓			
		ASCS (5-30 kHz)	Quantitative Sediment Characterization			✓	✓	
		Subbottom Swath System (1 kHz)	Shallow Subbottom Inhomogeneities		✓			
	Seismic Reflection Profiling	Surface-Tow Single Channel	Deep Sediment and Basement Structure		✓			
		Deep-Tow Multichannel (DTAGS)	Detailed Sediment Structure (upper 500 m)			✓		
	Gravity/Magnetics	Gravimeter/Magnetometer	Basement Structure		✓			
SAMPLING	Sediment/Waste Pile	Piston/Gravity/Box Cores	Sediment/Waste Physical Properties, Biological Studies, Porewater Chemistry		✓	✓	✗	
	Water Column	Bottles	Water Chemistry		✓		✗	✗
	Benthos/Bacteria	Net, Trawls, Camera, Cores	Species I.D., Concentrations		✓	✓	✗	
	Suspended Sediment	Bottles, In Situ Pump/Filter Sys. Sediment Traps	Particle I.D., Concentrations		✓			✗
FIELD MEASUREMENTS	Hydrographic	CTD	Water Mass Structure and Stability		✓			
	Currents	Moored Current Meter Arrays	Current Speed/Direction			✓	✓	✓
		Floats	Dispersion Pathways		✓	✓		
	Sediments	In Situ Probes	In Situ Physical Properties		✓	✓	✗	
	Turbidity	Nephelometer	Concentrations of Particulate Matter		✓			✗
	Acoustic Backscatter	Benthic Acoustic Backscatter System (BAMS)	Acoustic Lithology				✗	
	Biochemical	Benthic Chamber	Respiration, Pore Water			✓	✗	
OBSERVATIONS	Bottom Photographs	Sediment Interface Camera	Geological/Biological Observations			✓	✓	
		Bottom-Triggered Camera					✓	
	Real-Time Video	TV Camera (ROV, Manned Submersible)	Geological/Biological Observations				✗	
MODELS	NRL Multilayer Model				✓			✓
	NRL Mesoscale Model					✓	✓	
	LES Nonhydrostatic Model					✓	✓	
	Carbon-Flow Model					✓	✓	
	Pore Water/Diagenesis Model					✓	✓	
DATABASES	Oceanographic (e.g., GDEM)							
	Geological							
	Geophysical							
	Bathymetric (e.g., DBDB-5)							
	HITS Ship Density							
	Etc.							

✗ Periodic Sampling/Measurements (*vis-a-vis*, one-time)

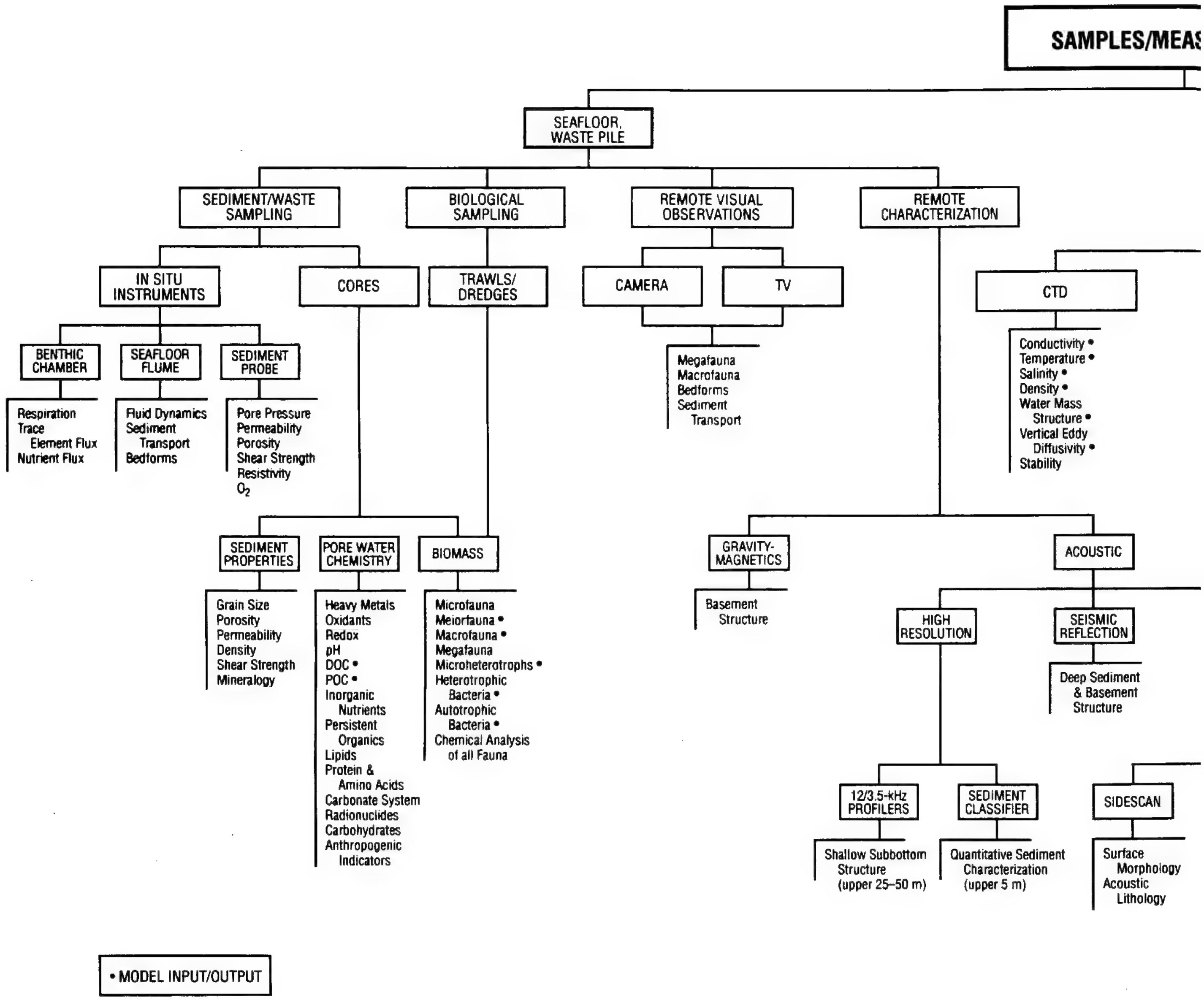
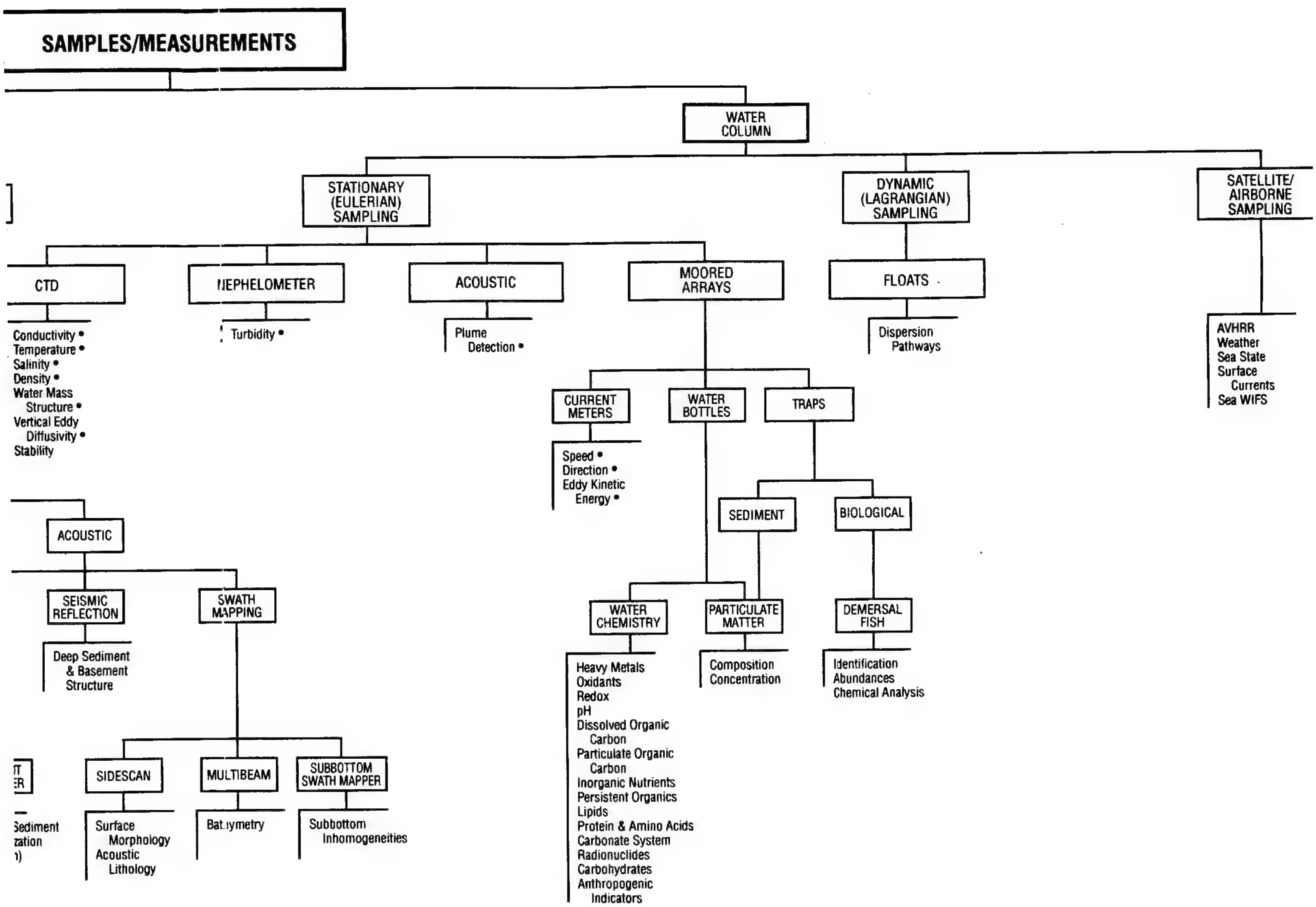
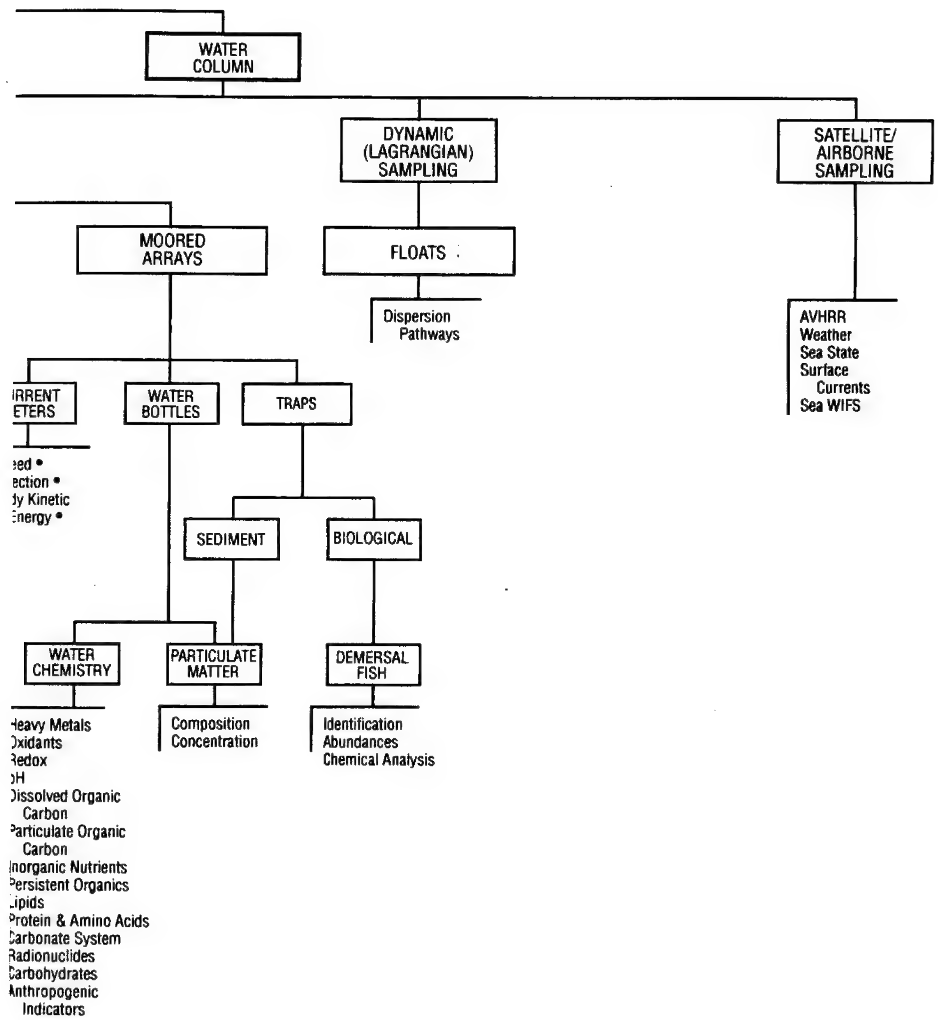


Fig. 4.4-1. Flow diagram showing organization of sampling ar



of sampling and measurement scheme for the sea floor and water column.



ı floor and water column.

To obtain 120% (overlapping) sidescan imagery, about 4 days are required, assuming a swath width of 10 km (5.4 nmi) and 12 parallel survey lines (using SeaMARC II or an equivalent system towed at 8 kt). Thus, a detailed bathymetric/morphologic survey will require about 9 days.

(3) **Seismic Reflection, Gravity, Magnetics**: Upon completion of the above surveys, it is recommended that the ship retrace the sidescan lines and simultaneously collect seismic reflection, 3.5-kHz reflection, gravity, and magnetics data. The time spent collecting these data is the same as the sidescan survey, i.e., 4 days. The 3.5-kHz survey is needed to resolve the fine-scale sedimentary structure of the upper 20–50 m of sediment and will complement the multibeam bathymetric and sidescan imagery data. The remaining surveys, particularly the seismic reflection survey, will provide information about the deeper sediment structures and the presence of near-surface, buried masses of crystalline basement rock. Faulting is commonly associated with sediments overlying basement peaks, and it is hypothesized that the faults provide pathways for the migration of pore fluids.

A complete, detailed geophysical survey of Tier II will take approximately 2 weeks, leaving about 2 weeks (assuming 4 weeks per cruise) for transit time to and from the site (about 5 days), unexpected problems (e.g., equipment downtime, repairs, etc.), or other operations such as deployment of oceanographic moorings. Thus, one 4-week cruise should be devoted to geophysical surveying.

4.4.2.2 Water Column Measurements

The dispersal of waste material around (near field) and away from (far field) the disposal site is controlled largely by the near-bottom currents. Thus, long-term current meter observations are required to (1) ascertain the temporal variability in direction and strength of bottom currents in and around the disposal site, (2) determine the likelihood of high-energy, transient events, and (3) validate circulation models.

(1) **Moored Arrays**: Long-term measurements call for the deployment of 1000-m-long moored arrays that are instrumented with thermistors, current meters, turbulence meters, tracer release units, transmissometers, water samplers, sediment traps, and cameras (Fig. 4.4.2-1). The suite of instruments is adapted from the recommendations in the Woods Hole Workshop Report (Spencer 1991) on abyssal waste disposal. It should be noted that the current meters will be a nonrotating type, such as acoustical or electromagnetic, since weak currents are likely to be encountered at most sites. At least five moorings are recommended. A suggested arrangement for the moorings is to place one mooring at each corner of the tier with a fifth placed at the exact center. The moorings should be deployed for 1–2 years with scheduled maintenance periods during this timeframe. Each mooring would take about 1 day to deploy, hence 5 days total plus about 1 day for transiting (6 hr between mooring sites).

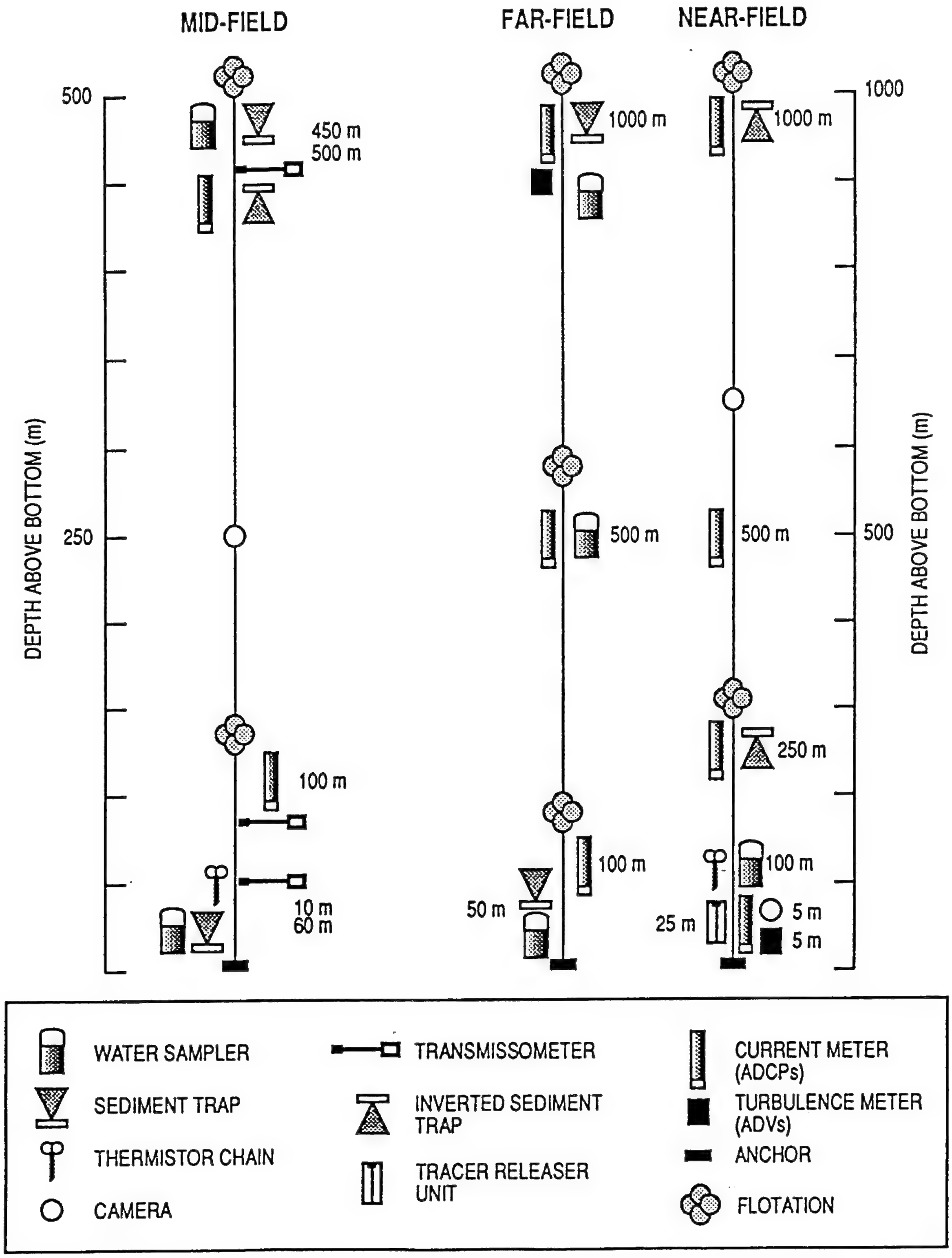


Fig. 4.4.2-1. Schematic of mooring arrays for disposal site.

(2) **CTDs**: A gridded series of 25 CTD casts would allow characterization of the water masses that comprise the water column at a horizontal resolution of about 15 nmi. Each cast would take about 3 hr with about 1.5 hr transit time between sites. Thus, the total time required would be about 5 days.

(3) **Floats**: After the CTD measurements, neutrally buoyant floats should be released in the water column as a means of characterizing the flow field at the site and validating model predictions concerning the dispersal of contaminants in the far field. We suggest at least three sets of 5 floats. One set should track within 100 m of the bottom; the other two depths can be selected on the basis of onboard analysis of the CTD data. A likely location for the release of the floats would be the center of Tier II. Release of the floats might require a few hours at most. Several means of tracking the floats are possible; one option is to equip the floats with transponders and track them with receivers/recorders attached to the moorings.

4.4.2.3 Bottom Sampling

The effect of waste disposal on the seafloor will be significant. It will immediately destroy the benthic fauna beneath the waste pile. Following this, the waste material and the sediments beneath will undergo gradual changes, both physical (compaction) and biochemical (redox); e.g., toxic substances may be mobilized and released to the water column and/or taken up by organisms, and the waste pile will eventually be recolonized. To assess these impacts it is necessary to establish requisite baseline information regarding the physical, chemical, biological, and biochemical nature of the sediments.

(1) **Cores**: A 4-week cruise will be necessary to sample the bottom sediments using gravity, piston, and box-coring devices. These samples should be subsampled, in turn, for geological, biological, and biogeochemical characterization. Coring should take place after the geophysical surveys are completed. This will allow preliminary examination and analysis of the underway data to select coring locations based on the acoustic lithology of the bottom. In addition to these specific core locations, core samples should also be distributed throughout the area to define gross sediment patterns. Thus, a gridded sampling scheme is suggested with some core sites being selected for the purpose of identifying specific features.

The majority of the sediment samples should be taken with a box corer that is capable of preserving the sediment/water interface. Moreover, the large sample volume (0.5 m × 0.5 m × 0.5 m) of box cores will provide ample material for the suite of geological, chemical (solid sediment and pore water), biochemical, and biological measurements summarized in Figure 4.4-1. In addition, a few long (10 m) piston or gravity cores should be taken for sampling the deeper sediments.

Assuming five cores per day (24-hr workday), roughly 100 cores could be collected during a 3-week period. This would result in a sampling resolution of about 7 nmi (assuming a uniform grid within a 60- × 60-nmi area). Taking into consideration that abyssal plains (as potential waste isolation areas) are relatively uniform in terms of sediment type,

100 cores would no doubt provide adequate samples to characterize the geological, biological, and chemical environment and to identify the dominant environmental processes in the area. In addition to box cores, extensive bottom camera surveys, baited traps, and trawl sampling would be used to assess the near-bottom biota of the site: bacteria, protists, meiofauna, macrofauna, megafauna, demersal fishes, and motile scavengers. Extensive replication would be needed to estimate population means of the major species of each group. Even if the fauna is fairly uniform throughout the site and no faunal "boundaries" are crossed, on the order of 5 to 10 replicates of the box corer in which the entire sample is used will be required simply for assessment of the mean density of the entire macrofauna assemblage within reasonable confidence limits.

(2) **Trawls**: In addition to box coring, megafauna should be collected with bottom trawls. Megafauna may redistribute waste material by reworking sediments during feeding activities or by migrating into and out of the isolation area. These larger bottom animals are not adequately sampled with box cores and must, therefore, be sampled by trawling.

The primary trawl would be a 3-m wide Sigsbee beam trawl, lined with 1-cm stretch mesh, used with a pinger to assure bottom contact. It would be towed for 1/2 hour per 1 km depth. In addition, a 40-ft otter trawl towed much the same way as the beam trawl would be used. It would have 2.5-cm stretch mesh lined in its cod end with 1-cm stretch mesh. Enough replicates would be taken in the site that one could be confident that close to 100% of the resident megafauna and demersal fish species had been sampled, and that population means could be estimated (trawl-caught means, not necessarily real means) of the dominant species to within 95% confidence limits. This would probably require at least 10 trawls. Each beam trawl would take about 6 to 10 hours total, with about 2.5 hours on the bottom. The trawls would provide numerous specimens on which trace contaminant studies could be initiated.

4.4.2.4 Modeling

It is important to recognize that simulation models are both an assessment and monitoring tool. Consequently, the sampling and measurement designs of a site assessment and monitoring program are, to some extent, based on assumptions and predictions (models) about likely responses of the environment to perturbation. Thus, modeling is needed both to control characterization studies and to examine sensitivity of input parameters. It is important also to recognize that models are not infallible and disagreement between prediction and observation (i.e., model verification) offers the opportunity of improving understanding as well as the model.

Several models, listed in Table 4.4-1, are used at appropriate stages during site assessment (as well as site monitoring) to predict critical aspects of the site environment. Among these are regional ocean-circulation models of which the following model is appropriate for simulating the horizontal and vertical dispersal characteristics within Tier II.

The **NRL Multilayer Model** is a primitive equation ocean-circulation model (see Section 5.1.2.1). By running the model in basin-scale mode the problems associated with specifying boundary conditions are reduced. The version used here is finite depth with at least six layers in the vertical and 1/8° horizontal resolution. Another candidate circulation model is the **Semtner-Chervin model** which is a level model with typically 20 levels in the vertical but coarser horizontal resolution, roughly 1/2°.

4.4.3 Tier III

It should be noted that in Figure 4.3-1, Tier III is shown as a single 0.1° square centered within Tier II. In fact, the evaluation of Tier II will most likely result in the selection of several Tier III areas. Each area, by virtue of its small areal size, will be subjected to survey and sampling operations designed to achieve even greater detail and resolution than required in Tier II. The objective of these operations is to quantify, as precisely as possible, the environment conditions at the exact sites proposed for waste emplacement and to resolve any remaining environment ambiguities at these site-specific locations.

4.4.3.1 Geophysical Measurements

To achieve the level of detail and resolution required in Tier III [about 100 km^2 (36 nmi^2)], deep-towed instrumentation is a necessity. By definition, the instrument packages are towed near the seafloor (50–300 m), thus, swath widths are usually less than 1 km (Table 4.4-2). Three types of surveys are indicated in Table 4.4-1. Major objectives of the surveys are (1) to search for anomalous seafloor and subsurface structures/ inhomogeneities not resolved by the Tier II survey and sampling operations and (2) to map the fine-scale seafloor relief to document the thickness, shape, areal extent, and compaction of the waste pile after emplacement.

(1) **Sidescan**: A deep-tow sidescan survey is necessary for resolving the microscale morphologic features at the seafloor. To mosaic the entire seafloor requires about 5 days, assuming a tow speed of 2 kt, a nominal swath width of 500 m along 22 parallel, east-west trending survey lines, and 2 hr per turn.

(2) **Seafloor Characterization System**: A high-resolution (15-kHz or greater), narrow-beam acoustic sediment classification system (ASCS) can be married to the sidescan package allowing simultaneous data collection; thus, no extra time need be allotted for this survey. The ASCS permits the prediction of near-real-time sediment acoustic and physical properties (reflectivity, impedance, attenuation, velocity, density, porosity, grain size, shear strength, and sediment type) in surficial sediments (acoustic penetration is about 15 m in soft sediments).

(3) **Subbottom Swath Mapping**: The subbottom swath mapping system is basically a sidescan that delivers low-frequency energy and permits mapping of seafloor and subseafloor structures and properties. Approximately 50 m of acoustic penetration is expected in soft sediment. A survey of this type should require about the same number of days as the conventional high-frequency, deep-tow sidescan survey, i.e., 5 days.

(4) **Multichannel Seismic**: High-resolution, deep-tow multichannel data collection is recommended along two orthogonally oriented sets of four, equally-spaced track lines. Allowing 2 hr per turn and a tow speed of 2 kt, this should take just under 2 days. Ideally, a complete geophysical surveying of Tier III could be accomplished in about 11 days. This does not, however, take into account deployment and retrieval of the equipment, equipment repairs, etc. Because of this, and the fact that several of the geophysical survey systems occupy considerable deck space, two separate cruises (one for Tier II and one for Tier III) should be devoted entirely to the collection of geophysical data.

4.4.3.2 Water Column Measurements

The water column measurements in Tier III are similar to those carried out in Tier II. The difference is that in Tier III the measurements are intended to establish site-specific environmental baselines and to validate the fit of these baselines into the framework of larger basin (i.e., Tier I) and regional (i.e., Tier II) studies.

(1) **Moored Arrays**: Three moored arrays will be deployed in Tier III. These will be identical in length and instrumentation to those already deployed in Tier II. Hence, 3 days are required for deployment. In addition, we recommend the deployment of four short (100-m) moorings for detailed measurement of the bottom boundary layer. Each will be equipped with an ADCP, water bottles, transmissometer, and sediment trap.

(2) **CTDs**: Five stations with one occupying the center of the site. Total time would be less than 1 day.

(3) **Floats**: Five neutrally buoyant floats set to track near the bottom and deployed at the center of the site.

4.4.3.3 Bottom Sampling

Bottom sampling in Tier III is also directed toward the purpose of acquiring site-specific data and baseline information. This is reflected by the deployment of additional specialized equipment not utilized under the Tier II sampling plan. In addition to those as follows, baited traps would be used to catch scavengers, and photographic coverage of the site would be accomplished by a complete photomosaic of the bottom with survey cameras. The photomosaic would be developed with multishot survey cameras such as a Benthos model camera loaded with 3,000 shots or a submersible used to travel over the whole site prior to the disposal. The photomosaic could be laid over the fine-scale multibeam survey of topography and a 3.5-kHz subbottom survey.

(1) **Cores**: As before, bottom sampling should take place after completion of the geophysical surveys and preliminary analysis of the data. A gridded sampling scheme is recommended. Sixteen-box cores spaced evenly over the area would allow a sampling resolution of 2 km and provide enough samples for geological, biological, and biogeochemical determinations. An additional 15-box cores should also be taken at specific locations, deemed optimal for waste disposal, to verify the macrofauna and determine faunal variability at tens of meters

scales, bringing the total number to 31-box cores for Tier III. This would take about 6 days to complete (same assumptions as with Tier II).

(2) **Trawls**: Given the expected low densities of abyssal seafloor biota, a few bottom trawls should be sufficient to verify that the megafaunal determinations derived in Tier II hold for Tier III.

(3) **Benthic Chambers**: Deployment of benthic chambers on the seafloor will provide direct measurement of fluxes of dissolved species (e.g., oxygen) across the sediment-water interface. These data, together with pore water studies, allow quantification of parameters that are essential for modeling reaction, migration, and release of waste contaminants to the water column under deep-sea conditions. Several 24-hr deployments are envisioned with perhaps 1 or 2 at each of the optimal waste locations identified within Tier III.

(4) **Flumes**: Flumes placed on the seafloor can be used to measure the erosional behavior of cohesive materials (e.g., critical erosion stress) and to determine rates of biochemical/organic fluxes across the sediment water interface. In the latter case, flux rates provide baseline information required to evaluate the effects of disposal on near-surface biochemical processes.

4.4.3.4 Modeling

Understanding the physical oceanography at the waste site is essential from the point of view of containment/dispersal of waste material. The water column measurements made in Tier III (and Tier II) will, in turn, provide essential data inputs (hydrographic and current) for model runs designed to simulate the transport of waste material away from a hypothetical waste pile. In addition to this, the deposition of waste on the seafloor will undoubtedly cause dramatic effects, such as compaction of the sediments, expulsion of pore fluids (due to compaction), changes in benthic fauna, and isolation of the sediments beneath the waste mound, followed by oxygen depletion in the sediments and changes in biogeochemical cycles. Thus, it is important to determine fluxes that occur in the unperturbed environment and how they may change with perturbation. The following models are applicable to the above considerations.

(1) **NRL Mesoscale Model:** This model, also known as COAMPS (Coupled Ocean-Atmosphere Mesoscale Prediction System), is most suited to study the dispersal of pollutants in the locality of the site. The model would be run in ocean-only mode. In this configuration it is a hydrostatic, primitive equation model with fixed, open or closed, horizontal boundary conditions. The upper boundary will require modification since it will not be at the sea surface for these experiments. The most difficult part of these experiments is specifying the boundary conditions, i.e., the larger scale flow field. To accomplish this the mesoscale domain sizes are chosen to encompass just a mooring array. This allows the data from the array to be used as boundary conditions, and for the larger domains, the inner arrays can be used to verify the model results. The waste will be simulated as a passive tracer with a specified source concentration and a decay rate that simulates an appropriate particle settling velocity.

(2) **Pore Water/Redox Model:** Sediment pore-water profiles of dissolved chemical species are obtained from sediment cores. The profiles are sensitive indicators of organic matter degradation in the sediments (Jahnke et al. 1982). Modeling allows the quantification of rates of organic carbon breakdown and consumption of various oxidants which control redox conditions of the sediments and, therefore, the rate of release of certain heavy metals or toxic soluble organics. The model is applicable in establishing baseline conditions regarding fluxes of major degradation products.

(3) **Carbon-Flow Model:** This model is a carbon-driven flux model of inputs (sources of energy) and outputs (fates) of organic matter to the deep sea. Observing the perturbation of the model with the introduction of waste material will help define what measurements should be made both in the field and in the laboratory.

4.5 Site Monitoring

4.5.1 Introduction

A comprehensive environmental monitoring program has several facets (compliance with regulations, model verification, etc.); however, the ultimate goal is the protection of the environment and protection of man from harmful pollutants. Here we are concerned only with assessing the behavior and fate (transport) of the waste material as well as the impact of the waste material on the biological community. Thus, we define monitoring as field investigations and modeling that are designed to determine the effects of waste disposal in (near field) and around (far field) a site vis-a-vis site assessment which employs field studies to establish environmental baselines for post-emplacement comparison, documentation of environment changes, and model verification. Indeed, the distinction between site assessment and monitoring is not well defined and the type of data collected for site assessment can also serve site monitoring. Consequently, the overall approach to monitoring is not unlike that devised for site assessment.

The general objective of a waste site monitoring program is to answer the following questions (1) what are the short- and long-term dispersal paths and fate of the waste and its components, particularly those that may persist in the environment, (2) can the waste material return to man, (3) what are the effects of the waste on the physical and chemical environment of the site area, and (4) what are the biological effects of the waste disposal?

4.5.2 Approach

Monitoring of any deep-sea site will involve a series of near-field and far-field experiments that are not unlike those used in Tiers II and III. The measurement techniques designated for near- and far-field monitoring (Table 4.4-1) are designed to sample the sediment, water column, and biota, measure the distribution and alteration of waste contaminants, and document possible deleterious effects on organisms. These determinations are, for the most part, accommodated by the near-field experiments that are conducted on and immediately around (1- to 2-km scale) the waste material. The far-field experiments (2–60 km), on the other hand, are intended to ascertain the spread, if any, of the waste

material away from the disposal site, determine the far-field ecological consequences, and assess the potential return transport of pollutants to man.

Sewage sludge contains both particulate and soluble components; consequently, it is necessary to consider effects in both the water column and at the seabed. All techniques listed in Figure 4.4-1 are thus of potential use. Biological measurements provide information about effects of the waste material on the benthic organisms; biogeochemical measurements provide data on sediment and water quality, changes within the waste pile, and bioaccumulation of contaminants. Physical measurements will provide information about waste pile morphology and areal extent, plume behavior in the water column, and dispersal of contaminants.

4.5.3 Near Field

Near field is defined here as the area of the seafloor that is within a radius of about 2 km from the center of the waste pile. Clearly, in the event of continued dumping, the near-field radius would change. In the following sections we have furnished estimates of required number of moorings, cores, etc. It is recognized that the results of the actual site assessment studies will bear significantly on determining the required sampling strategies.

4.5.3.1 Geophysical Measurements

Mapping of the waste pile will be achieved with the following deep-tow, high-frequency acoustic survey instruments.

(1) **Deep-Tow Sidescan**: Will be used to determine the location, thickness (height), and areal extent of the waste pile relative to the disposal site boundaries.

(2) **Deep-Tow Sediment Classification System**: High-resolution, normal incidence acoustic techniques will be used to document the geotechnical behavior of the waste pile and surrounding sediments in addition to evolution (compaction, flow) of the waste pile after emplacement. Both of the above systems can be married eliminating the need for separate surveys.

(3) **Sector Scan**: High-frequency acoustic systems, towed near the sea surface, have been used to identify and track concentrations of suspended material in shallow water, i.e., plume tracking (Tsai and Proni 1985; Tsai et al. 1992). Similarly, a high-frequency (at least 100 kHz) acoustic device towed at depth and capable of sweeping areas of the water column would allow one to ascertain plume structure at abyssal depths.

4.5.3.2 Water Column Measurements

Effective monitoring can only be achieved if the dispersion of the waste material, or lack of dispersion, can be accurately determined. Dispersion of the waste around and away from the main disposal point will be predicted to a large extent by measurement of the bottom and near-bottom current field. Thus, long-term current measurements will be

required, particularly to establish that the waste material is not subjected to unexpected high-energy events causing erosion and redistribution of the waste. Material collected in sediment traps would prove an important aid in tracking the plume of fine materials. Water chemistry analyses of dissolved and particulate trace metals would aid in the tracking of plume material as well as quantify any release of contaminants from the waste material into the water column: in this case, it would be advantageous to add an inert tracer to the waste material at some appropriate time. A careful assessment of the system fluxes will also provide information necessary of predictive modeling of the long-term destination of contaminants. Water column chemistry should be based on routine sampling, particularly within and close to the benthic boundary layer.

(1) **Moored arrays**: We recommend three triangular sets of moored arrays consisting of a near-field array 2 km on a side, a midfield array 5 km on a side, and a far-field array 50 km on a side, as shown in Figure 4.5.3-1. Each array will be instrumented the same as the site assessment arrays (Fig. 4.4.2-1.). Deployment of the moorings will take about 9 days (1 per day) and should take place after the geophysical surveys of the waste pile. Moorings should remain deployed and maintained indefinitely, i.e., until it is firmly established that the waste is indeed contained within the near-field environment.

(2) **Floats**: Neutrally buoyant floats (approximately 5) will be released directly above the waste pile to monitor dispersion pathways away from the waste pile. The release of artificial tracers, in conjunction with the release of the floats, would provide another measure of dispersion and estimates of vertical diffusion.

(3) **CTDs**: The details of the water mass structure will have been sufficiently established during the site assessment phases conducted in Tiers II and III. A few routine CTD casts (6) should be made during each monitoring survey of the site.

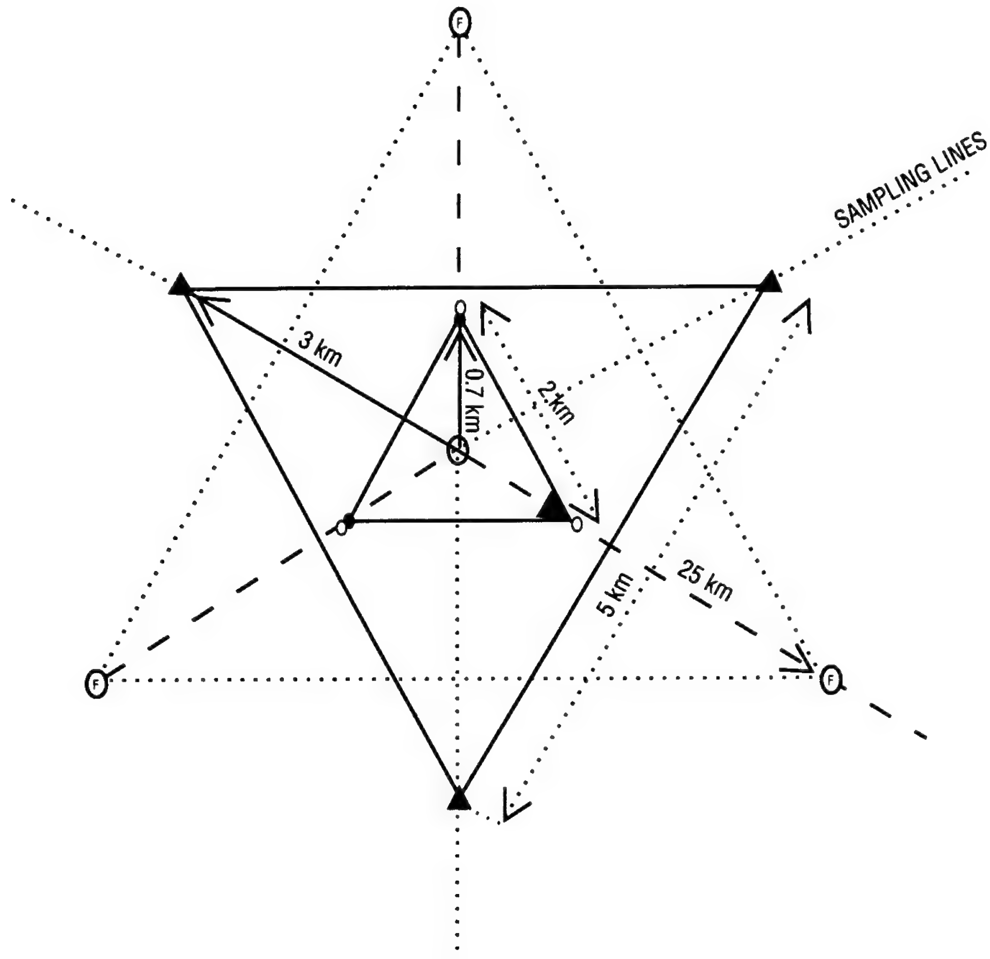
(4) **Transmissometer**: This instrument should be mounted in conjunction with a CTD. The optical detection (turbidity) of suspended material allows the possibility of assessing resuspension, horizontal dispersion, and eventual fate of the finer waste material transported by bottom currents (i.e., plume tracking).

(5) **Rosette:** A rosette water sampler should be comounted along with a transmissometer and CTD. The water samples will allow the levels of turbidity (as determined by a transmissometer) to be quantified as well as permit routine chemical analyses (salinity, oxygen, nitrate, phosphate, silicate, and dissolved and particulate organic carbon) of the water layers close to and above the waste pile.

(6) **Sediment Traps**: Downward opening sediment traps should be employed to measure the upward flux of waste material.

4.5.3.3 Bottom Sampling

Mapping of the waste pile and surrounding sediments can also be achieved by a combination of coring, photographic, and observational surveys. In the near field, the main waste pile will have a substantially different particulate composition compared to the surrounding



• ACOUSTIC BEACON Mooring	Instrumentation
o NEAR-FIELD	INVERTED SEDIMENT TRAPS, TRACER RELEASE CURRENT METERS, ADV-TURBULENCE, WATER SAMPLERS, THERMISTORS
▲ MID-FIELD	SEDIMENT TRAPS, CURRENT METERS, WATER SAMPLERS, TRANSMISSOMETERS, THERMISTORS
Ⓕ FAR-FIELD	SEDIMENT TRAPS, CURRENT METERS, WATER SAMPLERS, TRANSMISSOMETERS, ADV-TURBULENCE

Fig. 4.5.3-1. Arrangement of moorings

bottom sediment and should be easily identified. More importantly, the above techniques will provide the means to monitor the physical and chemical evolution both of the waste pile and the natural sediments over time. It is essential to know the extent of the affected area and the intensity of the effects. The problem of monitoring waste is difficult because the marine environment is complex and the waste is subject to progressive modification by physical, chemical, and biological processes occurring on and within the bottom. The sediment biogeochemistry in the immediate vicinity of the disposal site is likely to be severely perturbed. The biogeochemical environment in the upper sediment layers is primarily governed by a sequence of biologically mediated oxidation-reduction reactions (see Sections 1.5.6, 2.3 and 2.4). Changes in redox potential, due to a high oxygen demand of the waste material, will mobilize redox-sensitive elements such as iron, manganese, uranium, etc. Thus, an important environmental feature to be monitored is dissolved oxygen within the water column and the associated changes in the sediment. Bioturbation will likely be an important process returning contaminants to the biosphere, and the chemical aspects affecting the ecology of any recolonizing community should be carefully studied. Studies of the biota (infauna, epifauna, meiofauna, and microbiological fauna) may provide the most sensitive indices (e.g., changes in community structure, physiological and biochemical changes within species) to identifying and measuring the extent of the perturbations. As in the case of the water column, knowledge of the system fluxes will be necessary for predictive modeling.

(1) **Cores**: Box core samples of the waste material and surrounding sediments will provide the raw material for the physical, biogeochemical, and biological measurements outlined in Figure 4.4-1 and above. We recommend two suites of box cores; one suite taken on the waste pile itself and one in the surrounding sediments, each suite consisting of at least a dozen cores. Assuming, again, 4 hr per core with 1 hr for setup time and transit between core sites, 24 cores would take about 5 days.

(2) **Visual Observations**: Photographic surveys (bottom-bounce camera, camera-mounted sleds, tethered vehicles) or observations from submersibles provide first-hand information concerning the integrity of waste containers, recolonization, and behavior patterns of individual species. Visual surveys should be conducted immediately after emplacement of the waste material and routinely every 3 months for the first year, thereafter, at 1-year intervals. At least 1 week of a 4-week cruise should be devoted to making and recording these observations.

(3) **In situ Measurements**: Direct measurements of fluxes across the waste pile/water interface and the extent of reactions at the interface and within the waste (e.g., clathrate formation) should be obtained through a measurement program of benthic chamber deployments in situ probe measurements. Chamber measurements in combination with pore water studies provide the only means of quantifying parameters essential for modeling the reaction, migration, and release of contaminants to the overlying water.

It is important to note that, in addition to visual observations, submersibles and remote vehicles (ROVs) can be used to collect short, small-diameter cores and make in situ measurements. Their use becomes a virtual necessity in the event that the waste material placed on the seafloor is contained in bags. For example, follow biochemical changes that occur within the bagged waste, it will be necessary to revisit the same bag several times.

4.5.3.4 Modeling

Both sediment geochemistry models and the mesoscale ocean-circulation model discussed in Section 4.4.3.4 are applicable to the monitoring of near-field effects. The sediment models are particularly directed, in one case, at the chemical degradation of the waste material (pore water/redox model) (see Section 5.3.4), and in the other case, at the biological/biochemical effect of introducing large amounts of organic material into the environment (carbon-flow model) (see Section 5.4.1).

In addition, a fourth model is introduced here that is suited to the study of the initial plume that would result from either the discharge of waste from a pipe near the seafloor or from bags rupturing on impact with the seafloor. The **Large Eddy Simulation Model** is a three-dimensional, nonhydrostatic, primitive equation boundary layer model with periodic horizontal boundary conditions. For this study, a 500- to 1000-m region would be used with an approximate 5-m resolution in the horizontal and vertical.

Lastly, sediment resuspension and transport must be examined to determine the impact of near-bottom currents, including possible rare near-bottom current events, acting on exposed surficial particulate material on the surface of the placed waste pile. Resuspension and transport models developed and matured under the Office of Naval Research's programs are available to be applied to the abyssal seafloor waste isolation problem.

4.5.4 Far Field

Far field is defined here as those areas of the seafloor that are outside a radius of about 25 km and out to a few hundred kilometers from the center of the waste pile. The main objectives of sampling the far field are to determine the distance to which contaminants and biological responses will be detectable around the disposal site and to determine what factors control this distance. To accomplish these goals, samples of the water and surficial sediments will be collected. Given the potentially large area of seafloor encompassed by the far-field definition, an entire 4-week cruise should be devoted to sampling and measurement.

4.5.4.1 Geophysical Measurements

High-resolution, 3.5-kHz profiles of the seafloor will be collected routinely during the course of transiting between water sample and core sample locations.

4.5.4.2 Water Column Measurements

The configuration of moored arrays shown in Figure 4.5.3-1 allows for monitoring the far field (25 km from center of disposal point). In the far field, the moored instrumentation consists principally of sediment traps, water samplers, and current meters (ADCPs) arranged such that sampling is concentrated within the bottom benthic layer where contaminant levels are most likely to increase due to dispersion. There is the strong possibility that the concentrations of particulate matter in the far field will be extremely small and will require

large-capacity water bottles or a deep-sea pump/filter mechanism that will process large volumes of water. If so, a question to be addressed is whether or not such small amounts of contaminants are harmful to the biota or to and man.

4.5.4.3 Bottom Sampling

The above concern regarding the concentration of contaminants in the far field applies as well to the bottom sediments and bottom fauna. For this reason, box coring is recommended to obtain large surface-area samples of the seafloor for faunal and biogeochemical studies. Samples should be collected throughout the far field. However, if it is determined that there is a preferred direction of near-bottom current flow, sampling will be concentrated in the down-current area with at least one transect of cores taken parallel to the flow. The length of the transect and number of cores will be dependent upon physical prediction (based on bottom current strength) of how far downstream the fine particulate matter is expected to disperse. Far-field samples can also be used to detect natural long-term changes in benthic community structure.

4.6 Site Survey and Monitoring Costs *by Philip J. Valent and Frederick A. Bowles*

4.6.1 General

Estimates of portions of the costs of utilizing the abyssal seafloor waste isolation option have been presented in companion reports: for construction and operation costs related to the concepts for loading, transporting, and emplacing the wastes see Hightower et al. (1995), and for transportation costs from the municipal waste collection points to port see Jin et al. (1995). This section attempts a projection of the costs of (1) performing the initial site assessment and (2) providing the necessary site monitoring after the waste is in place on the seafloor. This analysis will show that, while these costs are certainly substantial, when these costs are distributed as a tax-per-metric-ton or per- cubic-meter, they appear reasonable when compared to the construction and operating costs for the emplacement concepts. (Please note, no inflation factor is included in these cost estimates. It is assumed that the costs will be assessed to the waste source in year D, and that the revenues for monitoring will be invested at a rate of return equal to the inflation factor; thus, the interest will pay for the inflation.)

4.6.2 Cost Projection Elements

The two cost elements in this projection are the expenses for (1) the research vessel cruise for 28 days with full complement of crew, scientists, engineers, and technicians and (2) the costs for scientist, engineer, or technician labor with accompanying support costs for laboratory, computing, graphics, publishing, and other support. The cost of each research cruise, including three technicians in the vessel "rental," for a projected 28 days, including time for loading and unloading of research equipment and acquired samples, is estimated to be \$20K per day, for a rental cost for the vessel of \$560K per cruise. Each cruise is

expected to be staffed by 12 scientists/engineers working 10-hr days at a salary of $800 per day for a cost for scientific staff of $270K. Adding other costs for the scientist/engineer staff, such as $12K for travel to and from the port, $10K shipping of equipment, $10K for dockside support, and $10K for expendables, yields a total cost per cruise for the scientists/ engineers of $312K. Then the total cost per cruise is projected to be:

rental of vessel	=	$560K
scientist/engineer complement	=	$312K
TOTAL cost per cruise	=	$872K

To these "field" costs for making measurements and collecting samples must be added the shore-side laboratory costs for planning, sample analyses, analyses of field and laboratory data, and for development of findings, conclusions, and recommendations. The cost of staffing for this work and laboratory, computational, analysis, and reporting support is projected to be $200K per man-year.

4.6.3 Site Assessment

For the initial demonstration test, execution of the required site assessment for each abyssal seafloor waste isolation site is expected to require two years. The Tier II field work, requiring three research vessel cruises, would be conducted during the first year, and the much more geographically focused Tier III field work, requiring two research cruises, would be carried out during year two.

The costs for the first year, year D-2 (i.e., 2 years prior to the demonstration test), are projected to be:

1. Cruise 1	– geophysics orientation, high-resolution bathymetry	$872K
2. Cruise 2	– oceanography, circulation data for model calibration	872
3. Cruise 3	– geology, sediment adsorption potential, biology	872
4. Shore-side	– 12 scientists & technicians @ $200K per man-year	2,400
	TOTAL, YEAR D-2	$5,016K

For the second year, year D-1, the Tier III work would require two research cruises and 12 scientist man-years shore-side as follows:

1. Cruise 1	– physical oceanography, recover long-term data from moorings, refurbish and replace meters	$872K
2. Cruise 2	– biological oceanography, characterize benthic biology	872
3. Shore-side	– 12 scientists & technicians @ $200K per man-year	2,400
	TOTAL, YEAR D-1	$4,144K

4.6.4 Site Monitoring

For the first two years after beginning of emplacement at a site (assuming emplacement at a site is terminated one year or less from start of use of that site), adequate monitoring of that site will require two cruises for near-field effects and one for far-field effects, focusing on water column and surficial sediment contamination. Shore-side labor and laboratory costs are expected to decrease to 8 man-years at $200K per man-year. The cost per year then would be:

1. Cruise 1	– ROV sampling of water and sediments immediately adjacent to waste containers and contained waste, mapping of the waste distribution, and container condition	$872K
2. Cruise 2	– Oceanography in near field, installation and maintenance of instrument arrays	872
3. Cruise 3	– Far-field water monitoring for tracers for containment verification	872
4. Shore-side	– 8 scientists and technicians @ $200K per man-year	<u>1,600</u>
	TOTAL, YEARS D and D+1, EACH	$4,216K

Monitoring should continue on a yearly basis for 10 years after halt of waste emplacement. One cruise would recover and replace a set of long-term instrument moorings placed down-current from the waste isolation site, and would perform an ROV inspection of the site to assess container condition and degree of waste isolation. Shore-side, two man-years of labor will be required to analyze and report the field data and to perform necessary sample analyses. The expected costs per year are:

1. Cruise	– ROV survey and instrument mooring work	$872K
2. Shore-side	– 2 scientists and technicians @ $200K per man-year	<u>400</u>
	TOTAL, YEARS D+2 through D+10, EACH	$1,272K

The annual costs estimated above, $4.2M for each of the first two years and $1.3M for the following nine years, compare favorably with the $2M to $3M annual cost of monitoring the 106-Mile Ocean Disposal Site reported by Wayland (1992, p 114). Assuming the area of Atlantic-1 Surrogate Site to be the most likely location of an abyssal seafloor waste isolation site, probable transit distance will be 600–700 nmi (see Table 1.4.1-2) compared to the much shorter distance to the 106-Mile Site, accounting for part of the larger cost estimated for the first two years for the site.

4.6.5 Cost Assessment

Although in reality a much different means of paying for this site assessment and monitoring may evolve, this analysis assumes the waste source to be billed for these costs. Assuming payback of all costs at no interest, the following is calculated:

Year	**Cost**
D-2	\$5.0M
D-1	4.1
D	4.2
D+1	4.2
D+2 through D+10(\$1.27K per yr)	<u>\$11.4</u>
TOTAL	\$28.9M

Assuming that one Surface Emplacement system operating from the New York/New Jersey area was to carry its annual capacity of 2.3 million metric tons of combined sewage sludge and fly ash to this one site, the distributed cost per metric ton would be:

(\$28.9M)/(2.3M metric tons) = \$12.60 per metric ton

5.0 ENVIRONMENTAL FACTORS AFFECTING ABYSSAL SEAFLOOR WASTE ISOLATION

5.1 Abyssal Flows in the Northwest Atlantic, Gulf of Mexico, and Northeast Pacific: Potential Influences on Abyssal Seafloor Waste Isolation

5.1.1 Physical Oceanographic Measurements *by Pavel Pistek, Albert W. Green, and Curtis A. Collins*

5.1.1.1 Introduction

Knowledge of the physical features of the ocean environment is crucial for the assessment of abyssal seafloor sites that could be used for the isolation of waste material. Dispersal characteristics at abyssal depths are the most important, but the motions in the whole water column and the surface ocean conditions are also important in the transport and emplacement operations. In this section, we summarize the characteristics of the flow over the abyssal seafloor in the northwestern Atlantic, northeastern Pacific, and the Gulf of Mexico. Oceanographic parameters relevant to the isolation of waste material were obtained from presently existing databases and from scientific publications. These data are utilized together with geophysical and biological parameters in the evaluation and selection of optimal isolation sites. It should be noted that the oceanographic measurements in abyssal depths (especially in the benthic boundary layer) are very rare, and consequently, we have had to make assumptions to extrapolate the limited data over regions where no measurements have been made. These assumptions were based on results of measurements, numerical models, and published descriptive oceanographic data.

The site characteristics and related properties of material to be isolated which will need to be considered are:

(1) the solubility and density of the waste material,
(2) the water depth at the site and its distance offshore,
(3) the presence of buoyant substances in the waste material, and
(4) the dispersal characteristics at the site.

The first three points are addressed in the OTECH engineering report (Hightower et al. 1995) in the sections on **Waste Stream Analysis** (Section 1.3) and **Site Selection Model** (Section 3.3) and in Subsection 5.1.1.2(3) in this section dealing with the creation and dispersion of the plume. The following are discussions of the factors that cause and control the dispersion of dissolved and suspended substances. These factors are applied to a brief description of the expected tendencies in dispersal of waterborne substances in the abyssal northwest Atlantic, the Gulf of Mexico, and northeast Pacific.

5.1.1.2 Dispersion and Factors that Control the Spreading of Dissolved and Suspended Substances

Material that is dissolved or suspended as small particles in the water column is subject to transport by the flow in which it is embedded. The process of dispersion occurs because

of the superposition of many scales of motion within the flow; these include advective flow, turbulent flow, and molecular diffusion. Each process is described further in Subsections 5.1.1.2(1) through 5.1.1.2(4).

(1) Advective Processes Generated by Steady and Low-Frequency Flows

Advection is the name given to fluid flow at relatively large-scale motions that can be characterized in terms of:

(a) mean flow, and

(b) fluctuations that are:

- periodic – seasonal changes,
  - – wave/wave-like motions that include internal gravity waves,
  - – tides, inertial (gyroscopic) waves, and topographic waves;
- nonperiodic – turbulence, eddies, and large-scale random events.

Currents near the bottom are the principal means of dispersion of waterborne material. They (1) enhance the diffusive exchange of material on the interface of deposited waste and the seawater, (2) enhance dispersion of material in the water column by displacement and intensified turbulent diffusion, and (3) create intense velocity shear that can reach the critical levels and resuspend the sediment. The mean flow (the time-averaged resultant of all of the flow components) provides a reasonable basis for estimating the range of dispersion of waterborne substances. Even when the mean current is quite small, the resulting displacement of a water parcel by the flow can be significant, i.e., a 1-cm/s mean current yields a mean displacement of about 300 km in a year.

The periodic fluctuations of currents about the mean speed are caused by several processes. In the abyssal ocean the principal periodic fluctuations are due to tidal processes, and to lesser extent the natural oscillatory modes of the basin (ocean seiches) and internal-inertial gravity waves. These fluctuations of the abyssal currents are important because they can add the critical amounts of energy in the turbulent, small-scale flow components that cause resuspension of sediments, mixing and dilution of the dissolved/suspended substances, or the delay of isolation of suspended particles.

In addition to these fluctuations with periods that range from the order of an hour O(hour) to the order of a day O(day), there are other waves with characteristic periods that range from O(> day) to O(months). These fluctuations are usually subdivided according to the dynamical forces and balances.

For example, the periods of the numerous components of the tides are determined by the gravitational forces on the oceans exerted by the Earth-Sun-Moon system, the changes of their relative positions, and Earth's rotation. The dominant components have semidiurnal and diurnal periods, and the relative energies are determined by the location and basin geometry. The tidal cycle is almost periodic at about 28 days, and about 18 years are required to repeat the "grand" cycle of all of the components. In the North Atlantic, Gulf of Mexico, and Pacific abyssal areas under consideration, measurements of tidal motions

are very rare, but in the reported cases for smooth areas, observed speeds have ranged from about 1 cm/s to about 5 cm/s. The typical tidal displacement is confined to an elliptical trajectory, so net displacement per tidal cycle is not large; however, the accumulated displacement can become significant and the tidal fluctuations can accentuate dispersion of suspended and resuspended materials. Measurements obtained near seamounts tend to have somewhat greater maximum speeds in the tidal period range, due to conditions imposed by the bathymetry. The periodic displacements of water over seamounts or at continental shelf edges also produce internal gravity waves over a broad spectrum of frequencies.

At abyssal depths far from their sources near continental shelf breaks and seamounts, internal gravity waves that are generated by tides are not a major source of disturbance of the benthic boundary layer; however, topographic and planetary waves could be sources of concern in selecting waste isolation sites. Topographic waves are generated, typically, by the meandering of a current system (i.e., Gulf Stream, Loop Current, California Current) over bathymetric prominences, such as continental slopes. Kinetic and potential energy are extracted from the current and the surrounding waters; the resulting fluctuating flow will have spatial scales determined by the bathymetry and the initial distributions of mass, kinetic energy, and latitude. Under some conditions the flow is "trapped," or confined, to move along certain bathymetric contours (Philander 1978). These trapped waves may have flow speeds that reach 0.3–0.4 m/s with periods ranging from days to O(month), so they could have major effects on the dispersion and dilution of suspended/dissolved waste materials. The problems that could be caused by these waves can be avoided by selecting sites that are not near continental slopes, major currents, or seamounts; this is a key element in our site selection process.

The major current systems (Gulf Stream, Loop Current, California Current) are subject to a variety of dynamical instabilities that cause the currents to meander, radiate waves, and create eddies. The radiated waves and eddies are of greater concern in the waste isolation problem, since they may add significant energy to the whole water column far from the sources where they were generated. There are two categories of eddies: *cyclonic* (counterclockwise elliptical flow with a dome of cold water at the center) and *anticyclonic* (clockwise elliptical flow with a thick lens of warm water at the center). Cyclonic eddies dominate in the North Atlantic, and anticyclonic dominate the Gulf of Mexico eddy distribution. Theory and limited experimental evidence (see following sections) indicate that mesoscale eddies tend to fill the entire water column as they evolve from their time of generation. Cyclonic eddies tend to lose their surface signatures. For the waste isolation problem, we would want to avoid the abyssal regions where eddy populations and energy densities are high. Measurements of the surface eddy distributions are facilitated by satellite-based measurement systems that provide good coverage during most of the year, and deep-eddy energy distributions have been obtained at a few sites using current meters. Numerical dynamical models have recently gained improved resolution and appear to have success in quantifying the eddy distribution statistics, but not the details of the vertical distribution of flows. The dispersion of waste materials from the isolation site by deep-eddy currents could be a source of problems, since the currents may persist for months with speeds that would be sufficient to carry suspended/resuspended/dissolved substances far from the site. Although comprehensive abyssal measurements of the eddy energy distribution have not been made, it appears that some abyssal regions are not seriously affected by eddies; consequently,

selection of sites for waste isolation and minimum probability for waste dispersion must be guided by the eddy energy distribution from measurements and high-resolution numerical dynamical models.

(2) Effects of Turbulent and Molecular Diffusion on Dispersion

In the previous paragraphs, the sources of fluctuations in abyssal flows, with periods O(hour) and greater, were listed and briefly related to the dispersion of substances away from a source of suspended or dissolved materials. Here, we briefly summarize the effects of spatially and temporally irregular fluctuations of much smaller scale. *Turbulence* is the term that is typically applied to natural, stochastic flow fluctuations at scales in time and space of O(seconds-to-hours) and O(10^{-2} m–100 m), respectively. Okubo (1971) has provided an excellent discussion of vertical and horizontal mixing in the oceans; the reader is referred to his work for a thorough summary of passive dispersion.

Dissolved or suspended substances embedded in turbulent flows will be subject to random displacements that will tend to mix the substances with the surrounding fluid, steadily reduce the concentrations of the substances by dilution, and disperse the substances over increasing area. At molecular scales there is also vigorous random motion due to thermal energy of the solvent molecules.

(a) Molecular Diffusion, Chemical Reactions, and Adsorption of Dissolved and Suspended Substances

At scales of O(10^{-3} m) and smaller, the random displacements of molecules leads to dilution of the dissolved or suspended substances. This dilution process by random displacements is called diffusion. In the case of molecular diffusion, the process is well understood, predictable, and is accurately represented by Fick's Law:

$$\frac{\partial C}{\partial t} = k_D \nabla^2 C ,$$

where C is the concentration, t is time, k_D is the molecular diffusion coefficient and ∇^2 is the rate of change of the gradient (the Laplace operator) of the concentration. Distributions of substances within a waste deposit will be altered by diffusion and reactions or adsorption within the deposit and at the water-deposit interfaces.

When a dissolved or suspended substance chemically reacts or adsorbs to the surface within the deposit, or at the water-deposit interface, it may be effectively removed from the diffusion-reaction process. These removal processes are represented by the addition of chemical kinetic and adsorption "sink" terms to Fick's law:

$$\frac{\partial C}{\partial t} = k_D \nabla^2 C + (\text{Reaction Kinetics}) + \text{Sinks} .$$

The principal effects of reaction and adsorption on the dispersion of waste material from isolation sites in the abyssal ocean are: (1) the removal of materials from the diffusion processes that would eventually allow some of the substances to escape to the ambient water, and (2) the alteration of rates at which the concentrations go to equilibrium with respect to conditions in the undisturbed ocean.

Fine sedimentary particles have a large ratio of surface to volume, so that they are extremely efficient at adsorbing dissolved substances from the water into which they are stirred. Natural clays, for example, have from 10 to 100 square meters of surface area per gram of sediment. They act like ion exchangers bonding chemically some ions present in seawater. They act more efficiently in their scavenging property in a turbulent environment because the diffusion of substances is enhanced. This way some elements leaking from emplaced waste piles may be captured and deposited in distant locations. Presence of the bottom nepheloid layer in the area of disposal would permit this form of dispersion.

The chemical reactions are influenced by temperature and to a smaller extent by ambient pressure. In the abyssal zones the temperatures are typically less than 2°C and pressure is about 300 atmospheres. Little is known about the chemistry of anthropogenic wastes under these conditions.

(b) Turbulent Diffusion Effects on Waste Dispersion

The displacement of dissolved and suspended substances by the random turbulent motions of seawater has some similarities with molecular diffusion, so this analogy is often used to approximate turbulent diffusion/dispersion; however, features of the mean, dominant flows and the random fluctuations must be included:

$$\frac{\partial C}{\partial t} + (\mathbf{U} \cdot \nabla)C = \nabla\ (k_T\ \nabla\ C) + \text{Sinks},$$

where $(\mathbf{U} \cdot \nabla)C$ represents the advection of concentration gradients by the background flow, and $\nabla\ (k_T\ \nabla\ C)$ indicates that the turbulent diffusion coefficient (k_T) is subject to spatial variations imposed by the structure of the turbulent flow. Sinks represent the chemical reactions, adsorption, and sinking to the seafloor of the substances; these processes may effectively remove the waterborne substances from the dispersion process. The turbulent diffusion/dispersion processes that would be expected in abyssal seafloor areas would be dominated by the relatively weak currents produced by tides, the general thermohaline circulation, eddies, and the instabilities of the bottom boundary layers beneath these currents.

The long-term distributions of waterborne substances are determined by the mean current, turbulent kinetic energy densities, and the processes that remove the substances from the water. In the past decades there has been little scientific interest in the details of near-bottom abyssal circulation, due to the difficulties and expense of long-term observations and the underlying, implicit concept that abyssal areas were virtually undisturbed by currents, except in the vicinity of major western boundary currents and near the connections with marginal seas. Records of near-bottom abyssal currents are very scarce, particularly

in areas that would be likely candidates for waste isolation. In the following sections we describe the results that we have extracted from the small number of current measurement reports that are available for the regions of interest. The accurate generalization of these results is subject to significant error in estimating dispersion of waterborne substances, since actual dispersion will depend heavily on several important factors that are not known.

The primary unknowns are the actual roughness of the abyssal bathymetry and the details of the effects of the bathymetry on the bottom currents. For example, waterborne substances released in an abyssal depression, with steep sides and with no passages for flow through the depression, would have minimum dispersion; however, dispersal of materials released in an open valley oriented in the direction of the basic abyssal flow would be somewhat greater. Recently, high-resolution sonar imaging systems have been applied to abyssal mapping in limited areas. Results of some of this work are presented in Section 5.2.1, **Bathymetry and Morphology**. Notably, bottom roughness measurements obtained by lower resolution systems were generally found to underestimate the complexity of the small-scale abyssal bathymetry. If plans for testing the feasibility concepts for abyssal waste isolation move beyond the paper study phase, then the site selection will depend heavily on the details of the local bathymetry. Another important consideration is the buoyancy of the released substances relative to the surrounding water. A buoyant solute or suspension could be convected high above the abyssal features and would be advected with the major current above the bottom. The buoyancy effects on stability of the isolation of wastes is critical.

(3) Buoyancy and Static Stability Effects on Dispersion of Waterborne Substances

Sewage sludge typically has a fresh water content of 70–80%; however, the strength of the hydration bonding in seawater at high pressure and low temperature is not known. Specifically, the rates of seawater replacement of "fresh" water in sludges and the kinetics of water release are not known. If the water contents of a sludge deposit were released entirely and quickly, then the buoyancy of the sludge water relative to the surrounding abyssal seawater could create a rapidly rising buoyant plume. The plume would rise to a level at which the surrounding seawater density and the density of the plume, which would contain a high proportion of entrained abyssal water, would be the same. The buoyant plume could greatly enhance the dispersion processes by spreading dissolved and suspended substances vertically in the water column. The fresh water plume would be expected to be dynamically similar to deep-ocean geothermal vents, "hot smokers," that are intermittent and sustained sources of superheated seawater. The geothermal plumes are under intensive study at this time; the observations and models could furnish working analogies for the fresh water plumes. Not enough is known about the "dewatering" of sewage sludge and dredged materials at abyssal depths to surmise the extent of the issue. Clearly, if the efflux of water from the isolation containers is rapid and volumetrically significant, then this factor must be considered in site selection/monitoring and the predictions of dispersion. The entrainment rate from ambient water to the plume and the maximum height of penetration are related to the static stability of the surrounding seawater.

In the abyssal depths of the oceans, seawater density is remarkably uniform; in the lower kilometer the relative change of density with respect to depth is O(1×10^{-8} g/m^3/m). Thus, stratification of density is very weak and the resistance to vertical displacements of a seawater parcel is accordingly small. The relative density change per unit depth is the static stability (E):

$$E = \frac{1}{\rho}\left[\frac{\partial \rho}{\partial S}\frac{ds}{dz} + \frac{\partial \rho}{\partial T}\left(\frac{dT}{dz} - \frac{d\theta}{dz}\right)\right],$$

where ρ is seawater density, S is Salinity, z is depth, T is temperature, and θ is the potential temperature (Neumann and Pierson 1966). In Table 5.1.1-1 the static stability is listed for the ocean areas under consideration. The restoring force of gravity in these weakly stratified conditions is very small, such that a water parcel that is displaced a small distance vertically would oscillate about its equilibrium position with a period of about a half day. This characteristic frequency is the Brunt-Vaisala frequency (N):

$$N = (g\,E\,)^{1/2}\ ,$$

where g is gravity acceleration. Under abyssal conditions, water and waterborne substances from sewage sludge deposits could rise hundreds of meters into the water column. The extent of convective plumes in dispersion of waste materials will have to be assessed empirically, since appropriate data about fresh water losses from sludge at abyssal depths are not available.

(4) Settling of Suspended Particles

As seawater flows over the abyssal seafloor, a thin layer of dynamical stress is applied to the particles at the sediment-water interface. If the flow is not too energetic and the bottom is smooth, this thin layer remains in a laminar flow regime in which the viscosity of the water and sediment balance the hydrodynamic stress. At the height of a millimeter or greater, this force balance is overcome by forces created by spatial and temporal fluctuations that lead to flow instability that evolves to turbulent mixing processes. Velocity increases linearly with height within the viscous layer and logarithmically in the turbulent layer above it. In the logarithmic zone, the properties of the water, such as salinity, temperature, and content of suspended solids, are actively mixed. This is called the *bottom mixed layer*. The top of the bottom mixed layer is usually considered to be the limit of thickness of the bottom boundary layer. It can extend to a few meters above the bottom if the flow is slow (O(cm/s)), and several tens of meters if the flow is rapid. Any stable stratification decreases the thickness of the mixed layer by requiring more work against gravity to achieve mixing. The rougher the small-scale topography of the sea bed and faster the overlying flow the greater the shear stress acting on the bottom sediments. Above a critical level of shear and roughness that can generate erosion processes, the rate of erosion rises exponentially with additional shear. Once sediments are freed from the sea bed they are acted on by opposing forces: turbulence tends to diffuse the particles upward and gravity causes them to settle. Deep-sea sediments typically consist of clays and fine silts whose particle size is less than 30 microns (μ). Such small particles settle slowly and their

Table 5.1.1-1. From Mantyla and Reid (1983) summarizing the range of values in the bottom kilometer of water for Northeast Pacific and Northwest Atlantic and McLellan and Nowlin (1963) for the Gulf of Mexico. The table shows water of very homogeneous structure with low stability.

North Pacific GEOSECS Sta. 216	Northwest Atlantic GEOSECS Sta. 30	Gulf of Mexico
40°46'N, 176°58'W	31°48'N, 50°46'W	Average from abyssal western Gulf
4725 to 5837 m	4786 to 5831 m	2000 to 3000 m
E = <0.8 x 10^{-8} g/cm^3/m	E = <1.7 x 10^{-8} g/m^3/m	E = <1.3 x 10^{-8} g/m^3/m
θ = 1.10 to 1.09°C	θ = 1.68 to 1.62°C	θ = 4.050 to 4.016°C
S = 34.685 to 34.684 psu	S = 34.866 to 34.857 psu	S = 34.971 to 34.973 psu

Table 5.1.1-2 Sinking speed of particles (bulk density 2.5) in still seawater with temperature and salinity characteristics typical of bottom waters

	Particle diameter (µm)	fall speed (cm s^{-1})	approx time to fall 100 m
	1	$5x10^{-5}$	6 years
Silt	5	$1x10^{-3}$	3 months
	10	$5x10^{-3}$	20 days
	50	0.1	1 day
	100	0.5	6 hours
	1000	15	10 minutes
Gravel	10000	100	2 minutes

concentration in the bottom mixed layer is nearly uniform in the presence of slow currents. As a result very fine material, once it is suspended, can be carried long distances by comparatively weak currents and can be observed as nepheloid layer in some areas of abyssal ocean. Likewise during the disposal of waste material, plumes will be created and the settling and dispersion of material will follow. Sinking rates (ν) of small particles may be predicted approximately from Stokes' law:

$$\nu = g\Delta\rho d^2(18\eta)^{-1}$$

where g is acceleration due to gravity,
$\Delta\rho$ is the density contrast between the particles and seawater,
d is the diameter of the particle, and
η is the absolute viscosity

(from Davis and Acrivos 1985).

Table 5.1.1-2 shows the sinking speed of natural particles in still seawater. The sinking speeds of sewage sludge particles are not necessarily represented by this formula, since they may be subject to rapid aggregation. Aggregation of particles causes a bulk response that usually increases the fall speed. The slow fall rates of fine clays that are the most common surficial abyssal sediment types, provide more time for the clay particles to adsorb and react with anthropogenic materials in the water column.

5.1.1.3 Circulation Characteristics

(1) Northwest Atlantic Abyssal Flow Characteristics

The North Atlantic Ocean is the most comprehensively observed and extensively studied of all the world's oceans, yet a description of the details of its large-scale circulation is not available. Clearly, the siting of waste isolation zone(s) in the abyssal oceans requires detailed quantitative information about the features of the abyssal flows. This section provides an overview of the results of observations and current conceptions about the interpretations of the available data.

(a) Abyssal Transport

Recently, a partly speculative summary has been given by Schmitz and McCartney (1993) as a synthesis of published research results from many independent investigations. They replaced the circulation regime hypothesized by Worthington (1976) by describing the thermohaline cell (thermohaline conveyor belt) connected to creation of about 13 Sverdrups (Sv) (Sv=$10^6 m^3/s$) of southward-flowing North Atlantic Deep Water compensated for in the upper layer by the northward cross-equatorial transport. Schmitz and McCartney (1993) proposed that the general circulation system has three major components (1) the Gulf Stream system (GSS), (2) a recirculating gyre north of the GSS, and (3) a southern recirculating gyre. Recirculations play an important role in deep-boundary current regimes and

in the formation and modification of water masses. The transport of the deep western and northern boundary currents in the North Atlantic may be doubled or tripled by counter-clockwise recirculating gyres and by addition of modified bottom or intermediate water.

Schmitz and McCartney (1993) depicted the circulation of the upper layer of 800–1000 m (temperature >7°C) (Fig. 5.1.1-1(a)), North Atlantic Deep Water (4–1.8°C) (Fig. 5.1.1-1(b)) and Antarctic Bottom Water (<1.8°C) (Fig. 5.1.1-1(c)). These depictions indicate the approximate transports, position, and spread of main surface and abyssal currents. Figure 5.1.1-1(a) specifies the sources of the well-established 30 Sv transported by the Florida Current off Miami (Schmitz and Richardson 1968; Richardson et al. 1969) composed of 13 Sv thermohaline cross-equatorial compensation for deep-water formation and 17 Sv compensation for the southward Sverdrup transport across 24°N (Schmitz et al. 1993). The transports near the Gulf Stream with recirculations are adapted from Hogg (1992). The C-shaped circulation east of the Bahamas is based on Schmitz et al. (1992), Reid (1978), and Stommel et al. (1978). Figure 5.1.1-1(b) shows the deep-water circulation as in McCartney and Talley (1984) and McCartney (1992). The amplitude of 13 Sv of the deep-water creation (6 Sv from NORDIC seas and 7 Sv in the Labrador basin) is augmented by 4 Sv of Antarctic Bottom Water admixture. In the midlatitude western basin the Deep Western Boundary Current is seen to divide. The direct path continues along the continental slope and the other branch turns toward the southwest onto the Sohm Abyssal Plain. The branches join southeast of the Blake-Bahama Outer Ridge. The bottom water flow pattern in Figure 5.1.1-1(c) was taken from McCartney and Curry (1993) and McCartney et al. (1991). An estimate of 4 Sv is crossing the equator. It flows westward into the Puerto Rico Trench. There are two exits from the trench, one onto the Nares Abyssal Plain through which bottom water as cold as 1.4°C passes to midlatitudes. A recirculation gyre lies over the Nares Abyssal Plain between the trench and Bermuda Rise. A second flow path is a loop through the Sohm Abyssal Plain east of the rise, first recognized by Wust (1935) as a principal northward flow route in the western basin. It is here that the bottom water mixes with the North Atlantic Deep Water forming the water mass with a characteristic temperature at 1.9°C. This picture of the flow of Antarctic Bottom Water is in good agreement with the Mantyla and Reid (1983) study of abyssal water characteristics.

The bottom currents interact with sediments through the bottom boundary layer and advect the leaking and dissolved material from the sediment below. The bottom turbulent boundary layer thickness is determined by the bottom roughness and the turbulent kinetic energy in the main flow above the bottom. Nominally the turbulent boundary layer thickness ranges from about 5 m with smooth bottom and low flow conditions to more than 50 m under high flow energy with rough bottom conditions. If the velocity of the current near bottom reaches the critical level (>10 cm/s) sediment erosion starts. Erosion can be caused only by energy that reaches the sea bed. The rougher the small-scale topography of the sea bed and the faster the overlying flow, the greater the shear stress acting on the bottom sediment becomes. Above the critical level of shear the rate of erosion rises exponentionally with additional shear. Once sediments are suspended they are acted on by turbulence and gravity. Deep-sea sediments consist typically of clays and fine silts whose particle size is less than 30 μm. Such small particles settle slowly and can be carried long distances by weak currents (Hollister et al. 1984). The High Energy Benthic Boundary Layer Experiment (HEBBLE) (McCave et al. 1978; Hollister et al. 1980; Nowell et al.

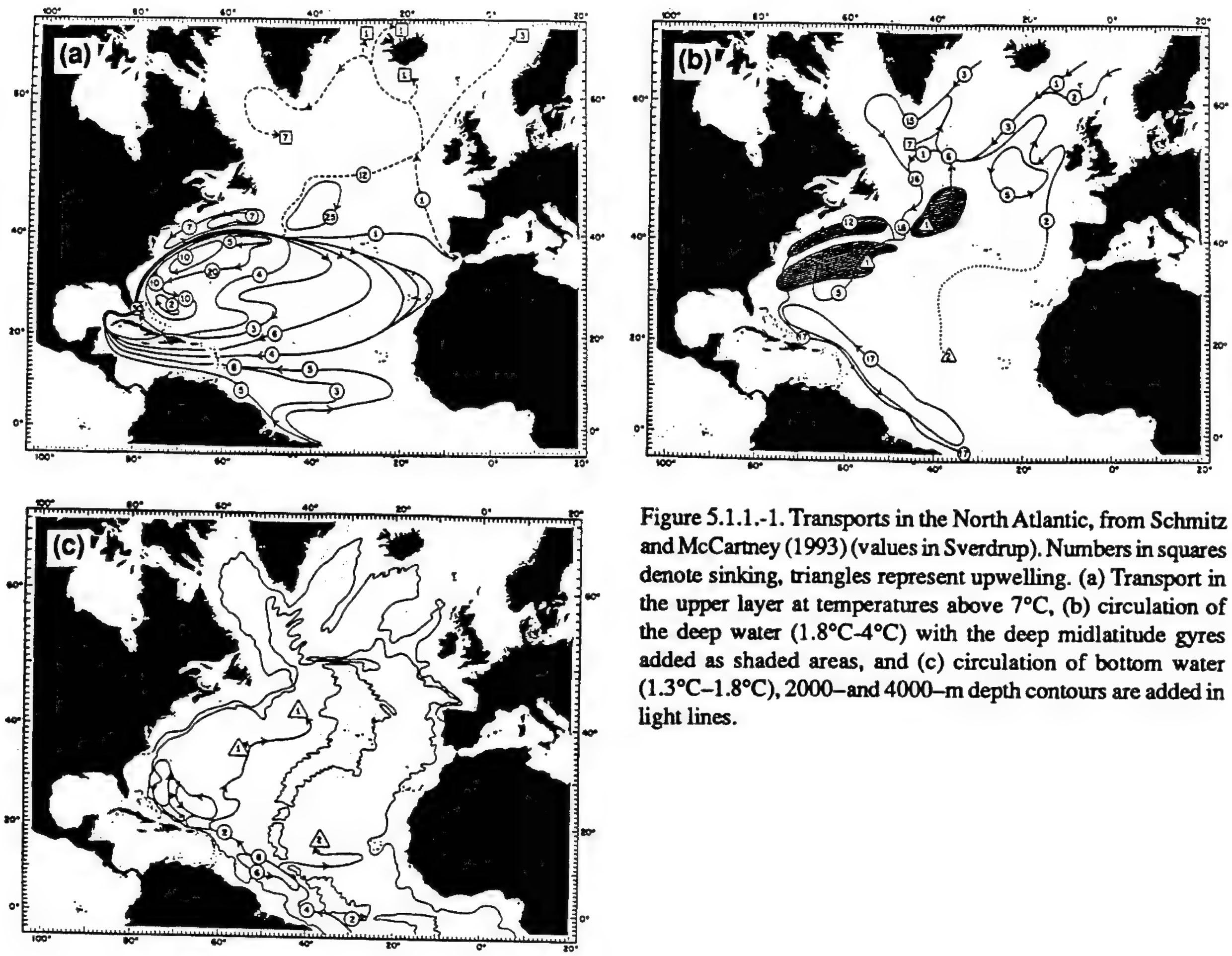


Figure 5.1.1.-1. Transports in the North Atlantic, from Schmitz and McCartney (1993) (values in Sverdrup). Numbers in squares denote sinking, triangles represent upwelling. (a) Transport in the upper layer at temperatures above 7°C, (b) circulation of the deep water (1.8°C-4°C) with the deep midlatitude gyres added as shaded areas, and (c) circulation of bottom water (1.3°C–1.8°C), 2000–and 4000–m depth contours are added in light lines.

1982) studied a bottom Ekman layer and sediment transport on the lower slopes of Nova Scotia Rise (Hollister and McCave 1984). They found very high bottom velocities up to 73 cm/s and suspended sediment concentrations up to 12 g/m^3. On the basis of the strong bottom current and its direction reversals, shown for example in Figure 5.1.1-2 from Hollister et al. (1984), they defined the periods of high currents as *abyssal storms*. The intermittently high currents persisted for periods of days to a few weeks. The high variability of flow speed and direction results in a high eddy kinetic energy (eddy kinetic energy does not signify only the mesoscale eddy origin, but rather the signals with periods longer than 2 days). The origin of this energy in the HEBBLE region was related to the high surface eddy kinetic energy of the Gulf Stream overhead. Weatherly (1984) showed the strong correlation between the presence of warm core rings produced by the Gulf Stream and presence of abyssal storms near the HEBBLE site. Pak and Zaneveld (1983) suggested that the turbid patches of water stirred up by abyssal storms and extending for a distance of about 30 km represent the interaction sites of warm rings with the bottom. Dickson (1983) showed that at the high-energy levels, the eddies should be more barotropic (more vertically homogeneous and not dependent on horizontal density gradients) and the flow depends only weakly on depth as shown in the Gulf Stream area by Schmitz (1980). Kelley and Weatherly (1985) made a comparison of long (8–12 months) near-bottom current meter records with satellite-derived frontal positions of the Gulf Stream meanders and rings and concluded that energetic fluctuations with time scales of 30–90 days resulted from the movement of Gulf Stream meanders and rings. Such benthic storms are not expected to be unique to the Gulf Stream area.

Klein and Mittelstaedt (1992) described similar events, with the velocities up to 27 cm/s and durations between 3 to 27 days directly above the deep seafloor, in the northeast Atlantic (45–49°N, 17–23°W). Abyssal waters are very weakly stratified in the bottom kilometer. This low stability permits the easier vertical mixing of dissolved substances or dispersed particles in the presence of disturbances (such as emplacement of waste material). Figure 5.1.1-3 shows the cross-section of concentration of variables in the northwestern Atlantic. Variations at abyssal depths between 4000–5000 m appears small in these low-resolution results. Table 5.1.1-1 summarizes the range of their values in the bottom kilometer; it also indicates that the Atlantic abyssal water is more stable than the bottom waters in the Gulf of Mexico or in the eastern Pacific.

Dickson et al. (1982) analysed the long-term current meter records (9–32 months duration) from the eastern North Atlantic (41–59°N), remote from the influence of the Western Boundary Currents. They found the strong *seasonal signal* in the baroclinic in eddy kinetic energy that is usually peaked in mesoscale length scales for all depths and is present in all sites. They concluded that energy at all depths in the eastern North Atlantic is a function of wind stress and stratification that is generated during the winter and early spring; energy continues to propagate to abyssal depths and decays to a minimum in late summer. Their model required some degree of bottom slope. This result is an important observation, from which it may be surmised that the eddy climate of the eastern midlatitude ocean is a function of windstress and stratification, not simply the synthesis of random mesoscale events. Koblinsky and Niiler (1982) suggested the same conclusion for observations east of Barbados, and it is surmised that the southeastern part of the northwest Atlantic has the same forcing. Looking at a few hundred current meter records of roughly one to two years'

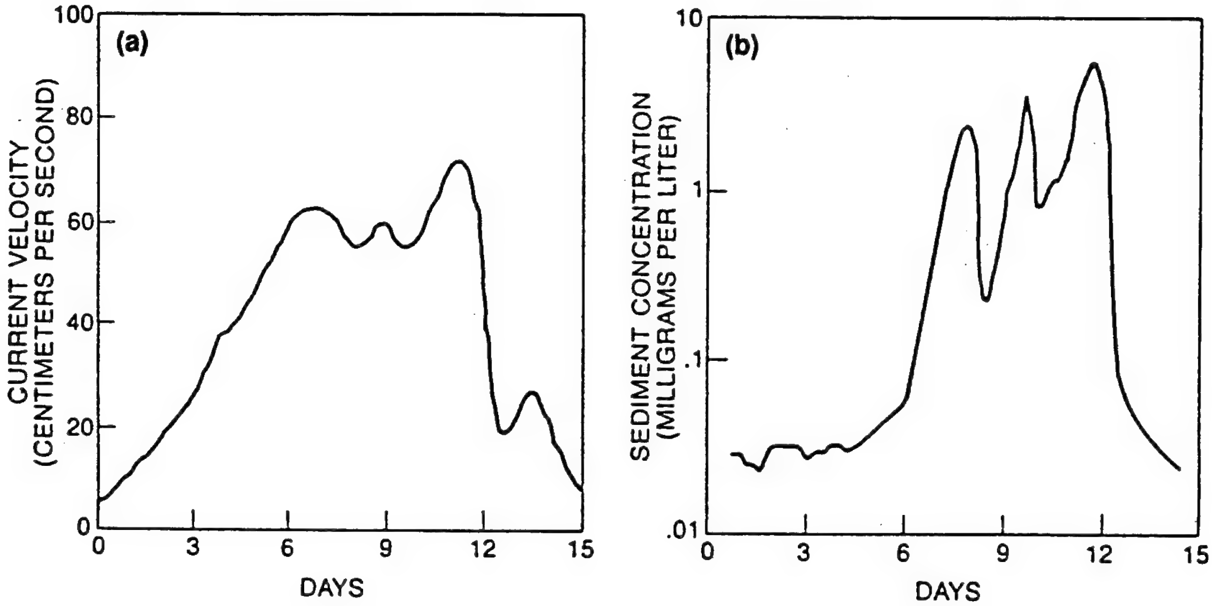


Figure 5.1.1-2. During a storm lasting for about a week: (a) the velocity of the bottom flow increased nearly tenfold, briefly exceeding 60 cm/sec (1.17 knots) and (b) simultaneously the concentration of sediment in the flow reached a maximum of 100 times the background (Hollister et al. 1984).

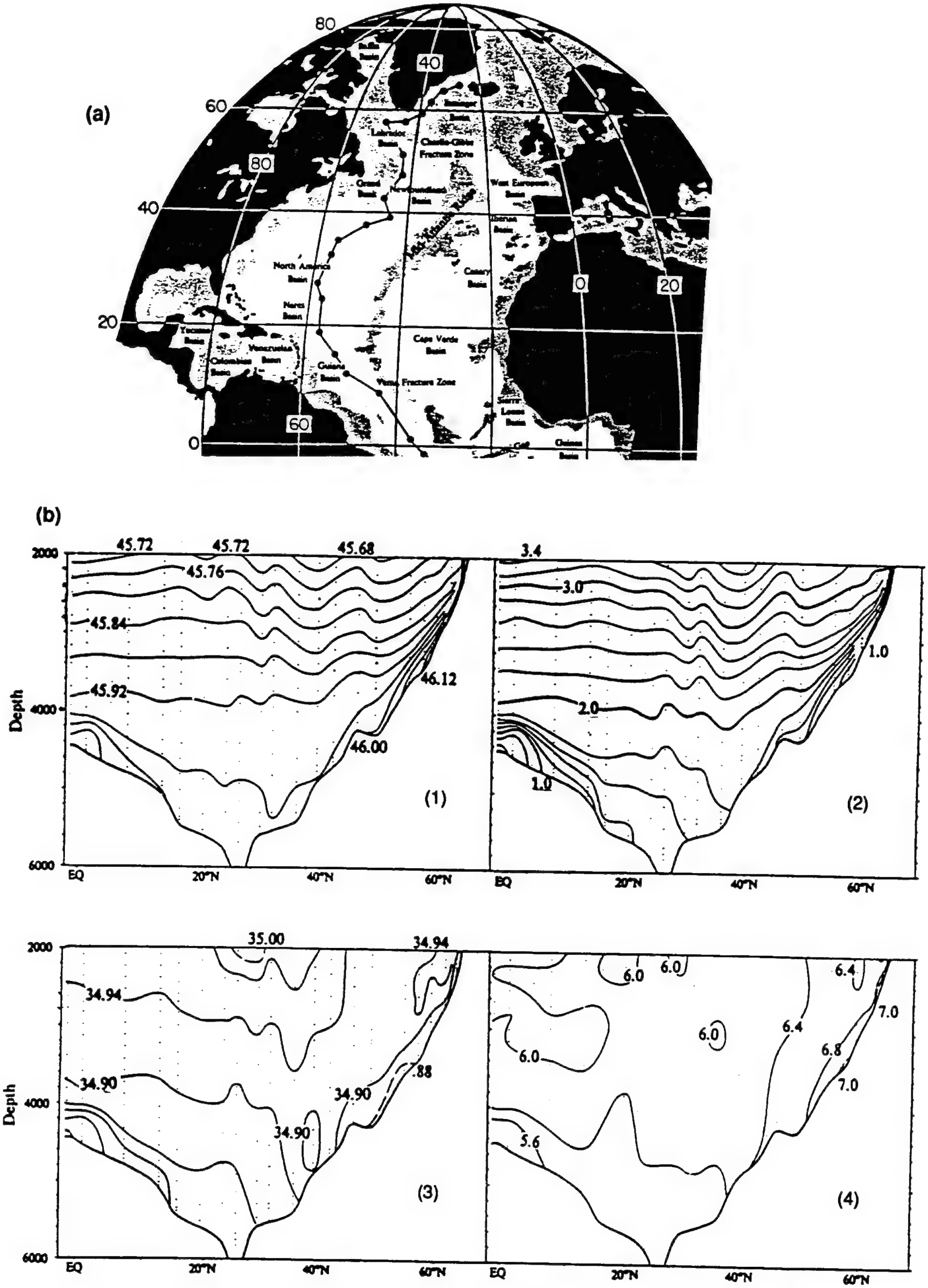


Figure 5.1.1-3. Western Atlantic Ocean section along the path of the densest bottom water. From Mantyla and Reid (1984). (a) Station locations are shown as dots and (b) cross sections of variables along (a). (1) density (σ_4) referred to 4000 db, (2) potential temperature (°C), (3) salinity (psu), (4) oxygen (ml/kg).

duration from diverse locations in the world's oceans, Schmitz and Luyten (1991) found that for the low-frequency ocean-current fluctuations, the shape of the spectra have a geographical distribution related to the general circulation. In the offshore segment of the Gulf Stream along with its recirculation areas, the normalized frequency distribution of eddy kinetic energy tends to be comparatively depth-independent and peaks at mesoscale (20–150 days). In areas distant from the strong currents, the normalized frequency distribution of eddy kinetic energy is baroclinic and peaks at the mesoscale at the abyssal depths. They also found that at depths near bottom relief, frequency distributions are energetic or peaked at periods on the order of days, which is an indication of the importance of topographic waves in the processes.

The locations of major resuspension under abyssal storms are likely to be those where the surface eddy kinetic energy is high and coupled to a strong near-bottom flow. A dense nepheloid layer would indicate the possibility of abyssal storm activity. Several authors using the Lamont nephelometer have demonstrated the clear relationship between the regions of high mean velocity in deep-boundary currents and the high suspended sediment content (Eittreim et al. 1976; Biscaye and Eittreim 1977; Kola et al. 1978). Regions of spreading of coldest bottom water (Mantyla and Reid 1983; Schmitz and McCartney 1993) and areas of isolation correspond closely (Heezen and Tharp 1977). Likewise the distributions of the highest eddy kinetic energy inferred from satellite altimeter (Cheney et al. 1983; Douglas et al. 1983) and ship drift observations (Wyrtki et al. 1976) coincide with the maximum turbidity.

The high horizontal eddy kinetic energy may also be accompanied by enhanced vertical eddy kinetic energy and thus higher vertical turbulent diffusivity. It has been suggested that the cross-isopycnal diffusivity (diffusion across density gradients) of 1–3 cm^2/s^2 identified by Hogg et al. (1982) and by Whitehead and Worthington (1982) results in the thickening of the nepheloid layer above the bottom mixed layer through upward diffusion of small particles (McCave 1983; Eittreim and Ewing 1972). Large concentrations of suspended particles were found on the western slopes of the northwest Atlantic and on the lower slope of the Bahama-Blake Outer Ridge by Biscaye and Eittreim (1974) and Amos and Gerard (1979). A major feature of the GEOSECS suspended sediment profile down the western Atlantic is the relatively high concentration extending to a depth of 2000 m between 35°N and 45°N (Brewer et al. 1976). This may contain material suspended from the bed and diffused upwards under high eddy kinetic energy of the Gulf Stream and warm-core rings on the continental rise or cold-core rings over the northern Bermuda Rise. The microscale particles of the deep-sea nepheloid layer have long residence times in suspension, O(1 year); thus, significant amounts of suspended material may have origin in resuspension far from the detection point. The emplacement or free-fall landing of a large waste container on the abyssal seafloor would create a disturbance of the surficial sediments that would result in a long-lived cloud of fine clay. It should be recalled that sedimentary particles have a large ratios of surface to volume so they are highly efficient at adsorbing dissolved substances from the water into which they are stirred. Natural clays for example have from 10–100 m^2/gm of surface area; and, if present in places of emplacement, they can efficiently adsorb and carry the dissolved pollutants. The level of the eddy kinetic energy is a good indicator for abyssal dispersion. Schmitz (1984) compiled maps of the distributions of eddy

kinetic energy in the North Atlantic from available abyssal current meter data. These maps, Figures 5.1.1-4(a) and 5.1.1-4(b), show the positions of the measurements with the eddy kinetic energy contours superimposed.

The basic picture of maximum abyssal eddy kinetic energy near the fully developed Gulf Stream is well substantiated by the current meter data, along with the two order of magnitude latitudinal decay in eddy kinetic energy (from about 100 to roughly 1 cm^2/s^2) into the interior of the subtropical gyre west of the mid-Atlantic Ridge. Eddy kinetic energy levels at abyssal depths near Cape Hatteras, in the vicinity of the Grand Banks, and west of the mid-Atlantic Ridge are down by one or two orders of magnitude from maxima near the Gulf Stream. Dotted lines in Figure 5.1.1-4(b) denote extrapolations. The mid-Atlantic Ridge does not appear to affect the energy level at 28°N. There are hints of an increase of eddy kinetic energy in the area near the North Equatorial Current. The location of the highest abyssal suspended sediment load (Hollister and McCave 1984) is roughly contained by the 100 cm^2/s^2 contour. This gives an empirical basis for estimating the long-term pattern of dispersal due to the abyssal circulation in this region. These broad distributions of kinetic energy distributions also provide indications about low-energy areas to be examined in detail, if pilot sites for waste isolation studies are to be found.

(b) Tidal Fluctuations

So far the discussion has been concerned with the low-frequency signals. In the studies cited so far, the tides and higher frequency fluctuations were removed from data, or were not considered. Tidal signal in the abyssal North Atlantic is small with the semidiurnal lunar tide (M2) as a dominant component. Luyten and Stommel (1991) compared M2 tidal components obtained from current meter records with the currents obtained from the Schwiderski global tidal model. The model currents conformed well with the observed data. The barotropic current speed for M2 in the abyssal ocean is smaller than 2.5 cm/s. The other tidal components were detected in current meter spectra with much smaller amplitudes than M2, so that total tidal currents do not exceed 3 cm/s in this area.

Internal tides can contribute to the current signal. Wunch (1975) and later Huthnance (1989) documented the widespread occurrence of baroclinic internal tides. [Baroclinic means that the density distribution couples with the pressure distribution to create the flow.] Hendry (1977) analyzed measurements of temperature and horizontal current fluctuations of the MODE data (28°N, 70°W) for semidiurnal internal tides. The M2 first mode internal tide was dominant and the horizontal currents in the barotropic and baroclinic tides were comparable with the characteristic abyssal amplitude of 1 cm/s. Internal tide was generated in the Blake Plateau escarpment area. Pingree and New (1991) observed the broad beam of internal tidal energy propagating down from the slope region on the upper continental slope of the Bay of Biscay, which after penetrating the deep-ocean interior reached the abyssal plain at a depth of about 4.2 km, 58 km from the source. The semidiurnal currents were noticeably increased near the seafloor. The bottom intensification of currents is often observed where the seafloor matches the characteristic slope; this effect is valid also for the downward propagation of internal waves. Enhancement of currents near the seafloor in abyssal depths was often observed in current meter measurements located near the seafloor (Schmitz and Luyten 1991). It is also common in the eastern Atlantic as

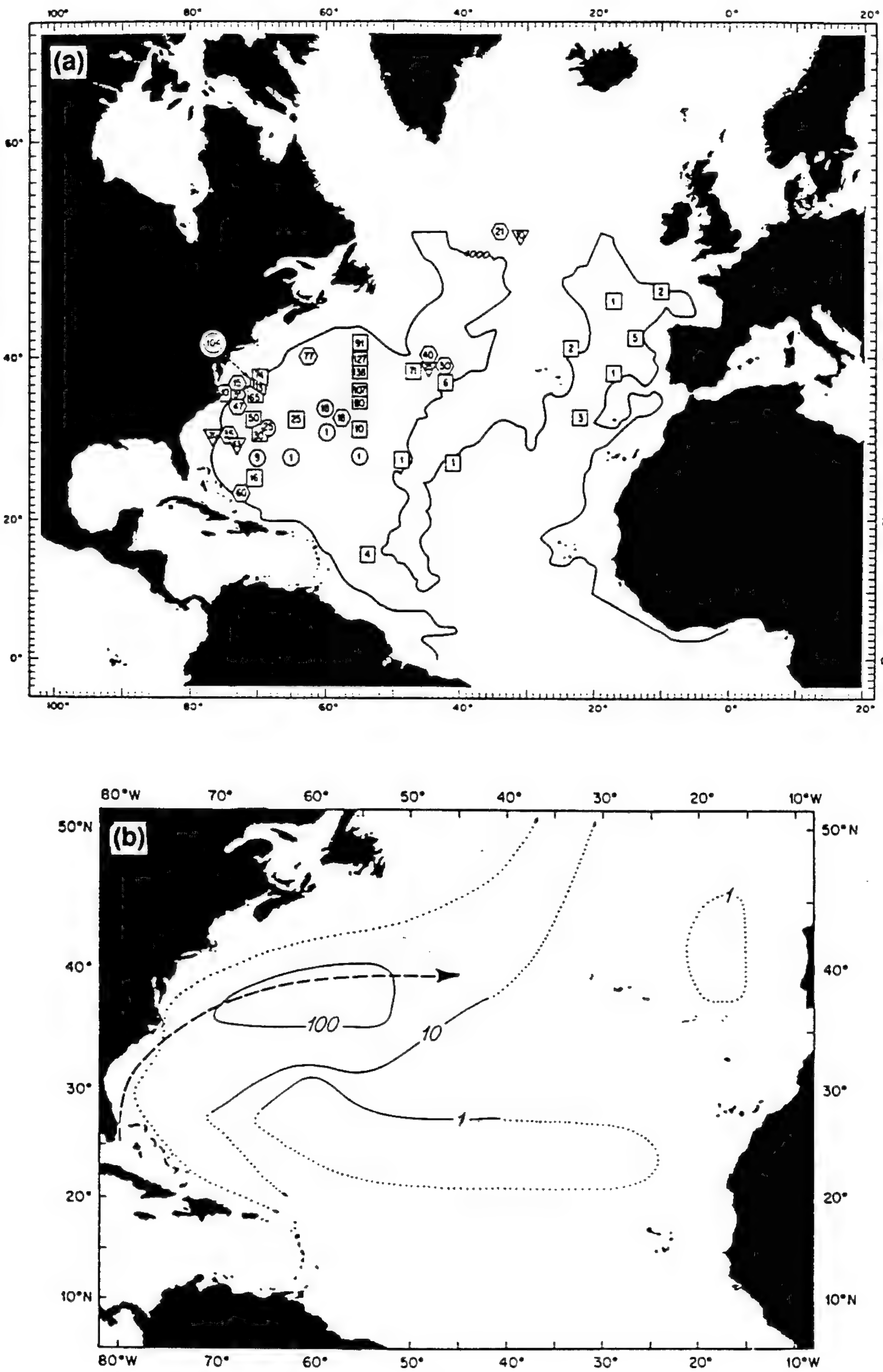


Figure 5.1.1-4. Contours of eddy kinetic energy in the Atlantic from Schmitz (1984): (a) observational sites and (b) contours of eddy kinetic energy in cm^2/s^2. Dotted lines show extrapolation and dashed line represents mean position of Gulf Stream.

described by Saunders (1986) for measurements near the sea bed on the abyssal plain in the Great Meteor East study site area (31.5°N, 25°W) and Vangriesheim (1988) in the Porcupine Abyssal Plain (47°N, 14.5°W).

The bottom current speed enhancement can be caused by bottom topography, but more complex forcing could be responsible depending on the geographic location. Highly energetic fluctuations associated with the topographic Rossby waves are frequently observed over the continental slope and rise off the U.S. and Canada with the energy source located at the eastward propagating meanders of the Gulf Stream (Bower and Hogg 1992; Pickart and Smethie 1993). The study of the mixing and circulation of West Atlantic Deep Water by means of the C_{14} method (Stuiver and Broecker 1975) showed that residence time in the area between 26°N to 56°N to be about 240 years. C_{14} overall residence time between 56°N and 30°S is about 340–380 years. This indicates that after about 200 years any material dissolved at abyssal depths of the northwest Atlantic spreads globally and after about 400 years would be present at the Antarctic Intermediate Water due to the upwelling in the southern circumpolar region. This result gives us some reasonable bounds on the structure and spreading rates of passive waterborne substances in these areas when considering the isolation sites.

(2) Northwest Atlantic Surface Circulation

In this subsection, the surface circulation is examined to identify regions of strong surface currents where the emplacement of material from the ships or barges could be jeopardized. In the Gulf Stream, and in the warm or cold core rings, the current speeds may exceed 150 cm/s. The geographic boundaries of the meandering north wall of the Gulf Stream are depicted in Figure 5.1.1-5 from Lybanon et al. (1990). Figure 5.1.1-6 shows the positions of detected rings during the 1967–1976 period (Kamenkovich et al. 1986). The area contained inside the envelope of the meandering Gulf Stream and the ring positions is not suitable for surface platform deployment. Figures 5.1.1-7(a) and 5.1.1-7(b) show the geostrophic surface velocity for summer and winter periods obtained from the Generalized Digital Environmental Model (GDEM). GDEM is described by Teague et al. (1990). These figures show the seasonally variable strong currents in the Gulf Stream and areas of its recirculation. Some features such as the C-shaped recirculation north of Puerto Rico (Schmitz and McCartney 1993) are recognizable, but the surface velocity field in the interior of the subtropical gyre is quite complex in comparison with the conceptual view offered by those authors.

(3) Gulf of Mexico Abyssal Flow Characteristics

(a) General Features and Water Types

The Gulf of Mexico is a semienclosed sea with total volume of 2.3×10^6 km^3 (Elliot 1982). It has two openings, the Yucatan Channel with sill depth of 1900 m and the Florida Straits with maximal depth of 800 m. Although the gulf is a semienclosed sea, it contains many of the circulation features that are found in the western Atlantic. The circulation of

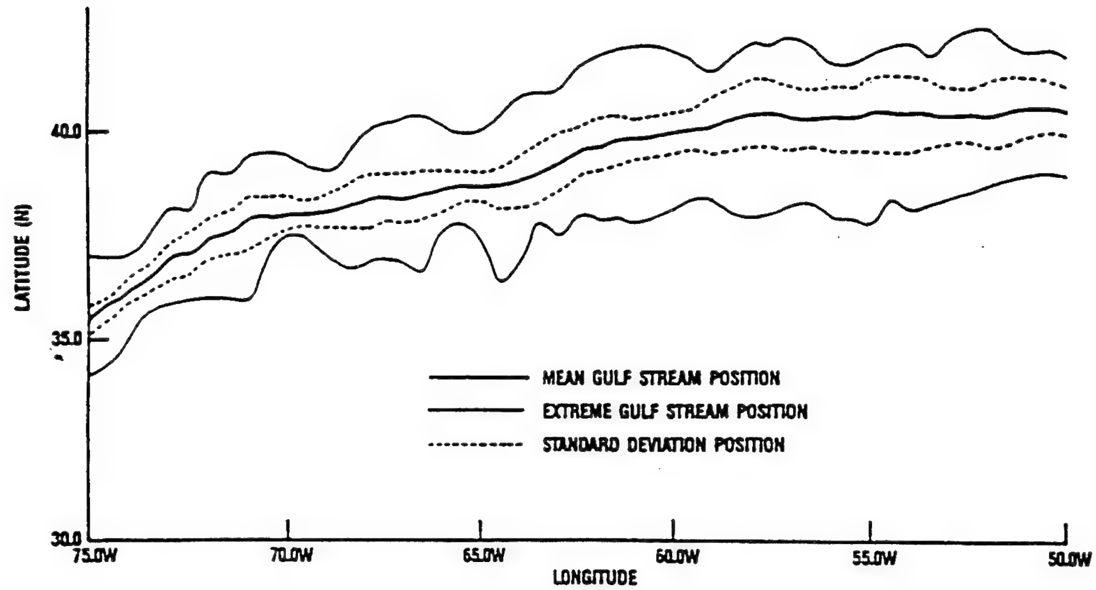


Figure 5.1.1-5. Geographic boundaries of the meandering north wall of the Gulf Stream from Lybanon et al. (1990).

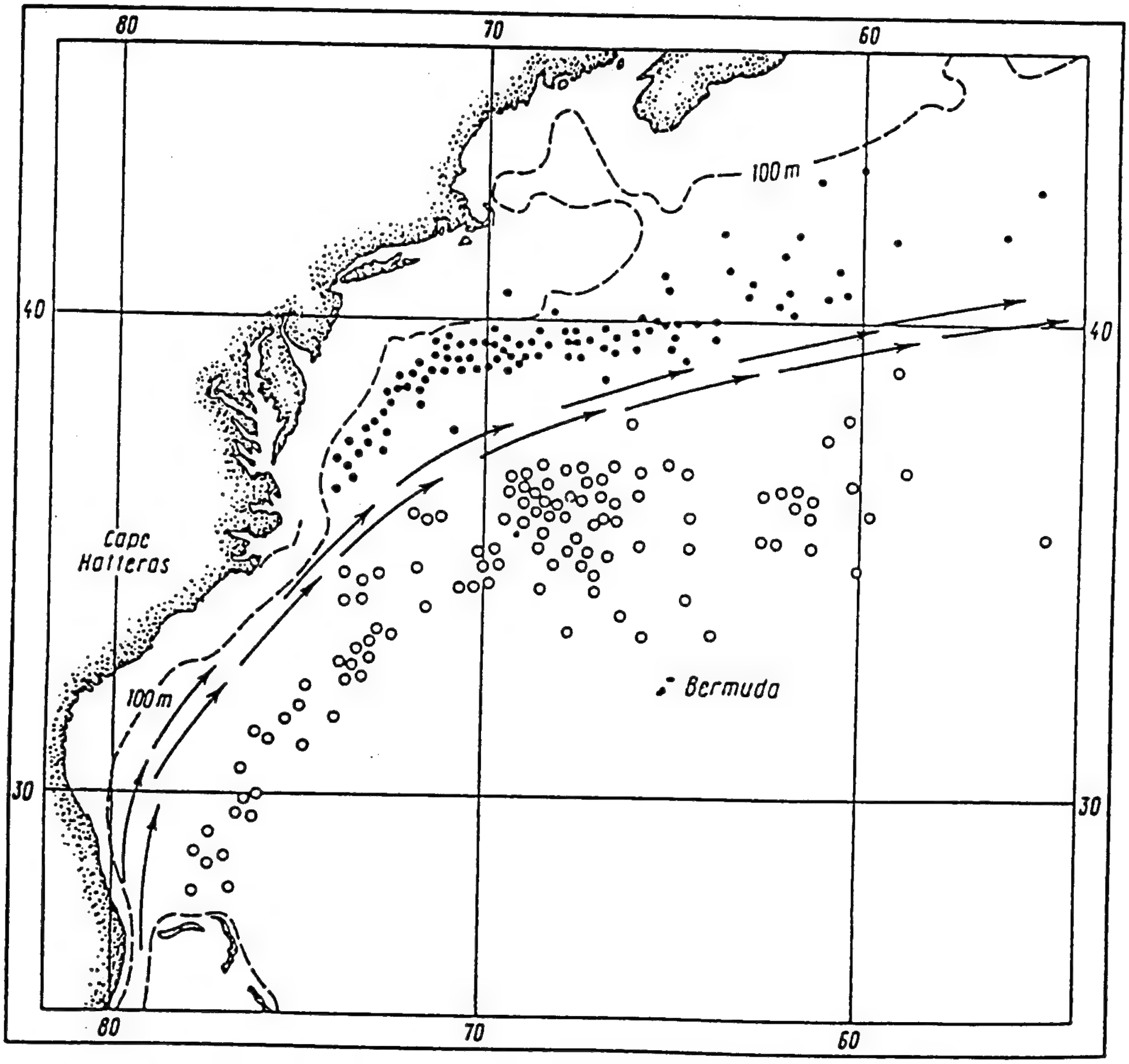


Figure 5.1.1-6. Positions of the centers of Gulf Stream cyclones and anticylones (light and dark circles, respectively) according to observations between 1967 and 1976 (Kamenkovich et al. 1986). If an eddy was observed several times, the chart shows the results of these observations. The arrows indicate the average position of the Gulf Stream.

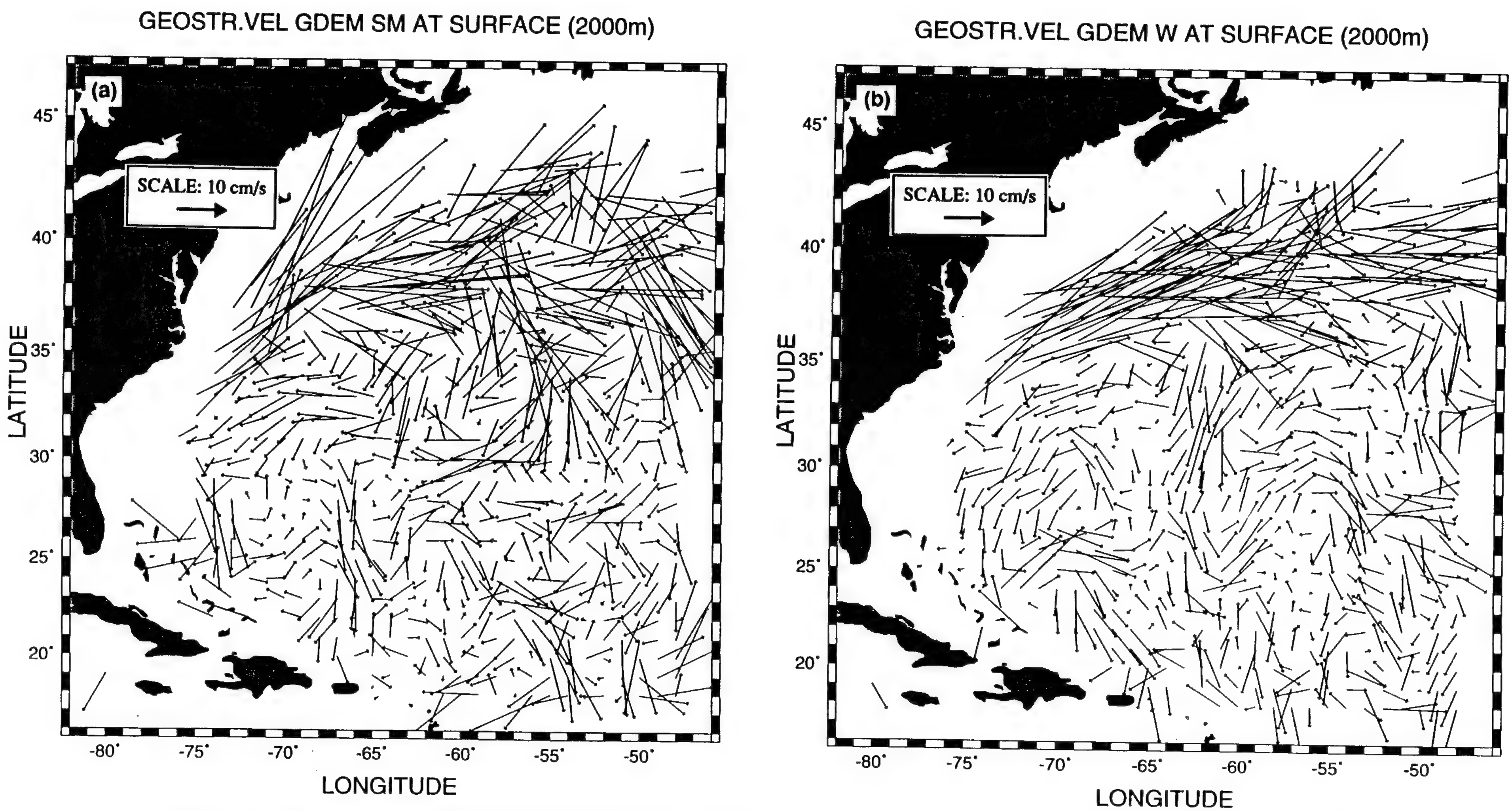


Figure 5.1.1-7. Surface geostrophic velocity 1°×1° in the Northwestern Atlantic, (a) summer and (b) winter obtained from GDEM data. Reference level 2000 m.

the eastern gulf is dominated by the Yucatan Current, which flows into the gulf through the Yucatan Strait, and the Florida Current, which flows out through the Florida Straits. The Loop Current is the clockwise flow that extends northward into the gulf and joins these currents. At times the Loop Current exhibits deep northward penetration into the gulf (Maul 1977; Vukovich et al. 1979). Several water types are involved in the gulf. Each of these water masses is found in the adjacent Cayman Sea and enters the Gulf of Mexico through the Yucatan Strait (Nowlin and McLellan 1967). The vertical salinity distribution from Hofmann and Worley (1986) along the Yucatan section is shown in Figure 5.1.1-8. Schmitz and McCartney (1993) describe in detail the upper layer contributions to the Yucatan Current/Gulf Stream system. About 13 Sv originate in the southern Atlantic and the remaining 17 Sv are North Atlantic Sargasso Seawater and water from the eastern portion of the subtropical gyre. The high salinity (high oxygen) water mass originating in the south Atlantic is an especially good tracer and indicator of mixing in the gulf. This water type has its maximum in the eastern gulf at about 200 m and disappears in the western gulf (Nowlin and McLellan 1967). Water with the salinity minimum, which is present between 800- to 1000-m depth, is the Antarctic Intermediate Water; and waters below, nearly isohaline, are consistent with the upper Deep North Atlantic Water mass.

The circulation in the gulf is dominated by the Loop Current and the large warm core (anticyclonic) rings created by the current's dynamical instabilities. The Loop Current transport is about 30 Sv with velocities of 1.5 m/s and higher. The warm core rings have the characteristic diameters of 200 to 400 km and propagate in the westward and southwestward direction into the western gulf, where they are the dominant circulation feature (Elliot 1982). Lewis et al. (1989) have shown that the interaction of warm core rings with the topography of the Mexican-Texas continental slope is complex, lasting over 6 months to one year, and is connected with the generation of vigorous secondary eddies (Brooks 1984). The translational speed of the westward drifting rings is 3–8 cm/s (Elliot 1982; Kirwan et al. 1984), and their swirl velocity is 50–140 cm/s (Elliot 1982). The rings are created at average intervals of 9 months. Because of the large size of the rings they have profound effect on the gulf's dynamics. Each ring contains about 7% of the gulf's total volume of water; thus, a significant fraction of the gulf waters are coupled with the anticyclonic ring processes. Assuming that a ring is formed every nine months, then the gulf basin volume could be replaced by 'ring water' in only 11 months. The upper ocean waters cycle through the gulf basin very quickly, but the abyssal water residence time is much longer.

(b) Factors Affecting Variability of Circulation

Precipitation and the river inflow to the gulf exceeds the evaporation by about 350 km^3/year. To balance the deficit of salinity in fresh water, about 0.74 rings/year are needed, which is well satisfied by the present production of 1.25 rings/year (Elliot 1982). Figure 5.1.1-9 from Elliot (1982) shows as an example position and extension of the Loop Current and rings in the gulf.

In the presence of strong eddy fields, a long series of current measurements are required to obtain a stable estimate of the mean circulation. Hofmann and Worley (1986) reanalyzed

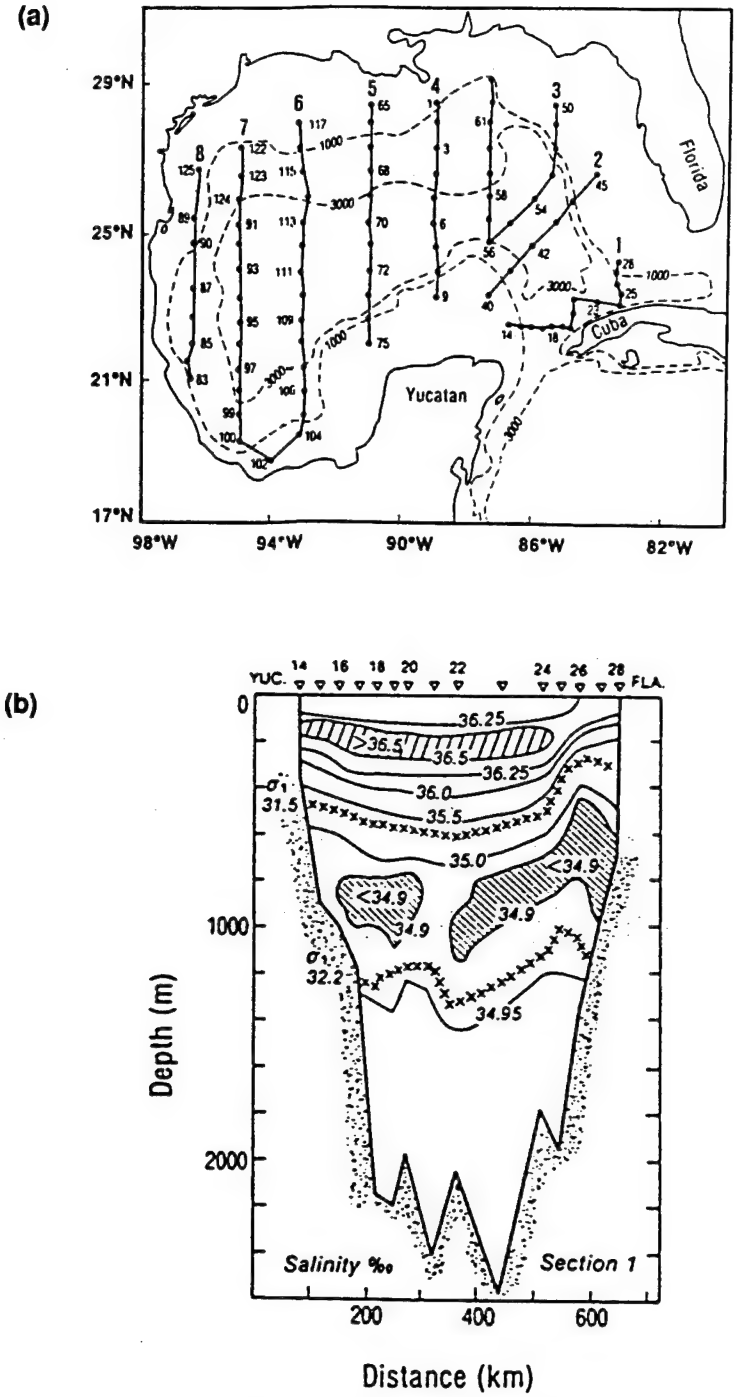


Figure 5.1.1-8. (a) Map of the Gulf of Mexico showing tracklines of the R/V HIDALGO, 12 February to 31 March, 1962 (Hofmann and Worley 1986). Far southeast trackline from Yucatan Peninsula to Florida is that for data in (b). (b) Salinity distribution for the Yucatan Peninsula to Florida section. The salinity maximum (upper hatching) that characterizes the Subtropical Underwater and the Salinity minimum (lower hatching) associated with the Antarctic Intermediate Water are indicated. The σ_1 surfaces (crosses) used to separate the water mass layers are shown. From Hofmann and Worley (1986).

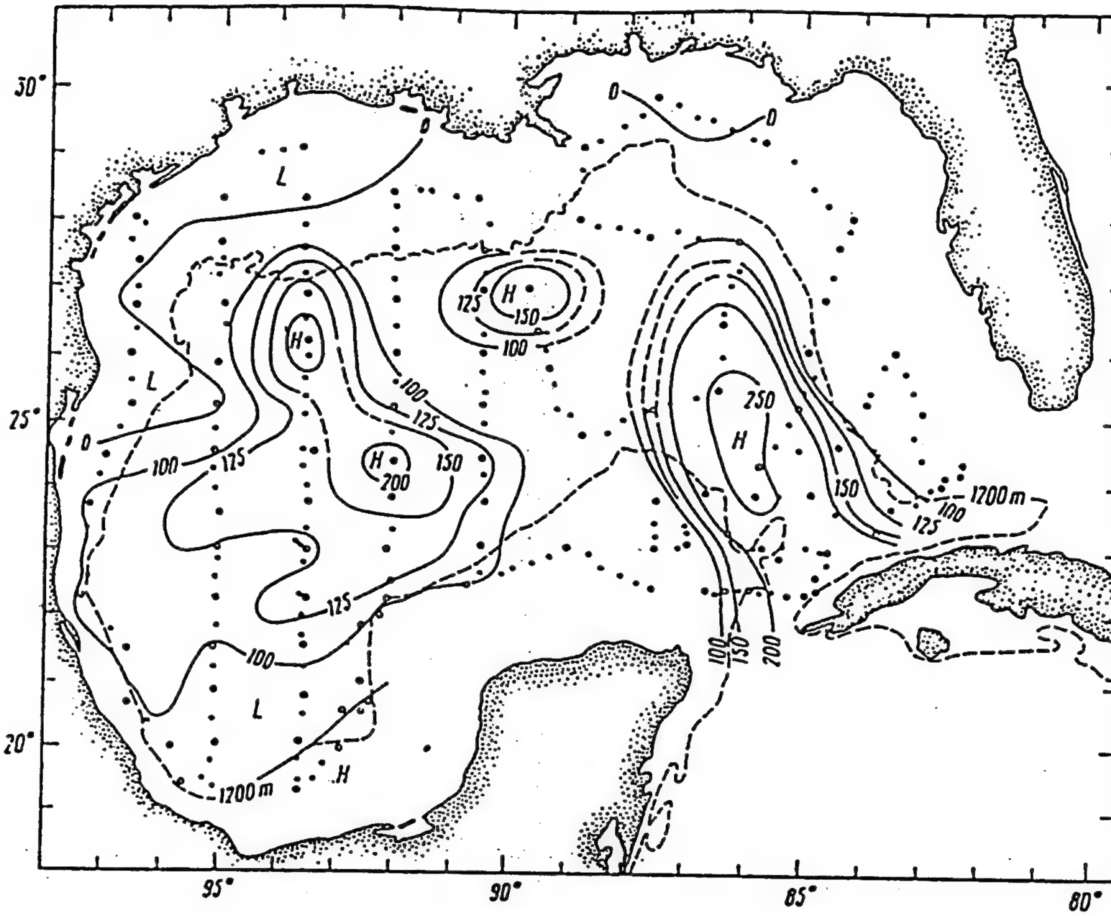


Figure 5.1.1-9. The 20°C isotherm depth (in meters) according to the data of the combined hydrographic and XBT surveys of the Gulf of Mexico (the light and dark circles, respectively), February 21–March 31, 1967 (after Elliott 1982). H and L show the centers of high and low pressures.

the historical hydrographic data obtained in the Gulf of Mexico using the inverse analysis. The results of their transport calculations are shown in Figure 5.1.1-10(a) and (b). Dominant circulation in the upper layer (about 1000-m thick) is anticyclonic with the wedge-like cyclonic cell south of Texas, while the deep layer shows cyclonic circulation under the anticyclonic surface gyre and more fragmented smaller circulation cells. Figure 5.1.1-11(a) and (b) represent surface geostrophic circulation computed from GDEM data with reference level at 800 m for summer and winter periods. It shows the dominant Loop Current in the eastern gulf and prevailing anticyclonic circulation in the western gulf with cyclonic cells embedded into it in the central gulf and stronger in the summer period.

The tidal components in the gulf's currents are small. Diurnal tide is dominant; the strongest tidal signal was observed in the Yucatan Strait, with an amplitude of 10 cm/s (Hansen and Molinari 1979). The baroclinic tidal motions were not evident in the gulf but are very large in the Florida Straits (Niiler 1968). There are only a few abyssal measurements. McLellan and Nowlin (1963) measurements below the sill depth (2000 m) indicated that the temperature and salinity vertical variation is small, although they found the average from many measurements yielded weak vertical gradients for these variables and slight positive stability (see Table 5.1.1-1). In contrast to the horizontal uniformity of temperature and salinity, the content of dissolved oxygen was nonuniform on all horizontal surfaces beneath the sill depth. Its horizontal distribution at 3000 m is shown in Figure 5.1.1-12. western central Gulf Deep Water (2500–3000 m) has pronounced oxygen minima. The same location of horizontal minimal oxygen content persists in medium levels. C^{14} dating for water collected at 3400 m in the minimum oxygen area showed an age of 519 ± 76 years (in McLellan and Nowlin 1963) while estimates of age for water at 1200–2500 m from the northwestern Atlantic and the northern Caribbean (which creates the deep gulf water) was 350 ± 100 years (Broecker et al. 1961). This is substantial evidence that the residence time of central gulf abyssal water is longer than that of the upper layer (~170 ± 100 years). One month of data from current meter mooring deployed at the central gulf (25°48′N, 89°44.6′W) to study internal waves showed at a depth of 2420 m maximum, current amplitudes of 35 cm/s (Saunders et al. 1980). This current meter was influenced by the Loop Current intrusion, indicating that the Loop Current can extend to 90°W. Hamilton (1990) measured abyssal currents in the eastern, central, and western gulf. He found that the major low-frequency fluctuations in the lower 1000–2000 m of the water column in the three regions have the characteristics of topographic Rossby waves, which are probably the results of dynamical processes that occur as the anticyclonic rings move on to the continental slope. The spectral peaks were observed at periods of 25 and 40 to 100 days. The Loop Current excursions into the eastern gulf, shedding of warm core rings, and the interaction between the rings in the western gulf are the energy sources generating topographic Rossby waves. Hamilton found maximum current speeds of 10–20 cm/s and near bottom current enhancement. He observed strong correlation between surface and abyssal currents in the eastern gulf and diminished coherence in the western gulf. He did not find evidence of the ring signal at abyssal depth in the central or western moorings. Nevertheless, it is possible that the ring did not pass sufficiently close to the mooring as the abyssal "foot-prints" of the warm core rings in the Atlantic are known to be about 30 × 30 km. There is other evidence from the current meter data of SAIC (1988) showing that the flow field of an eddy in the western gulf extended deeper than 3000 m. Likewise, Hofmann and

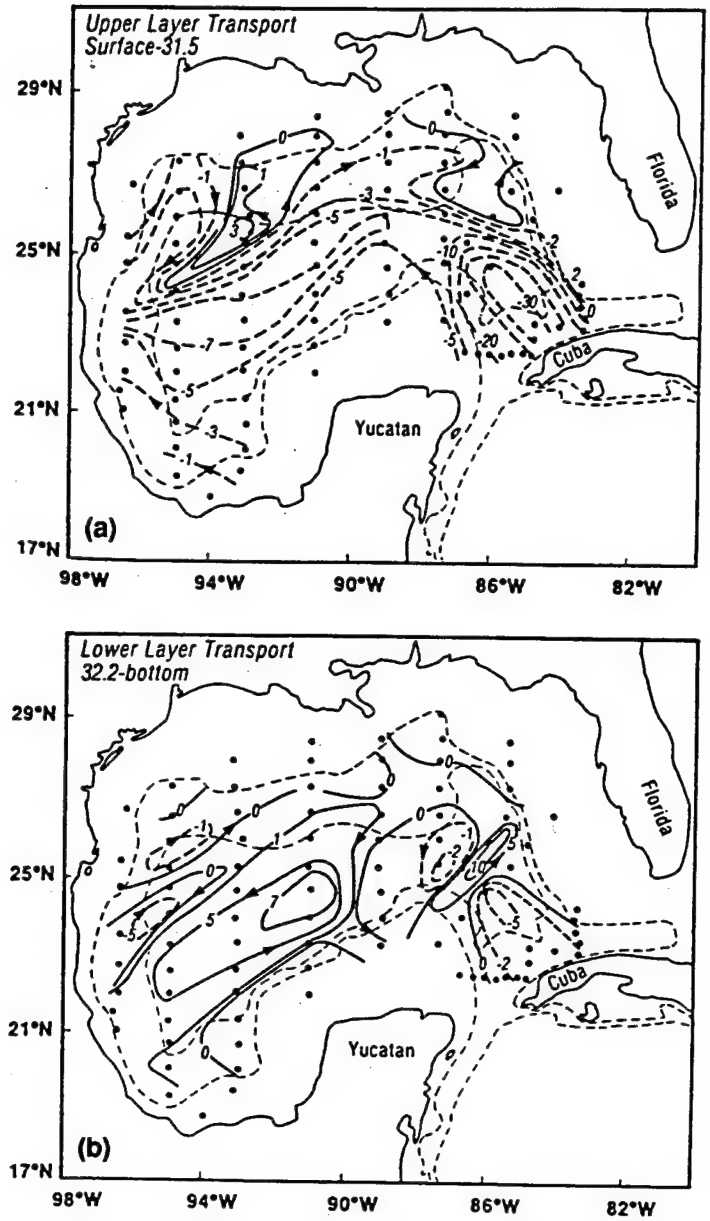


Figure 5.1.1-10. (a) Streamlines of volume transport for layer 1, which extends from the surface to σ_1=31.5. Transport values have been referenced to the southern end of the hydrographic transect. Dashed lines indicate clockwise flow. Solid lines indicate counterclockwise flow. (b) Same as (a) except for deep layer, which extends from σ_1=32.2 to the bottom. From Hofmann and Worley (1986).

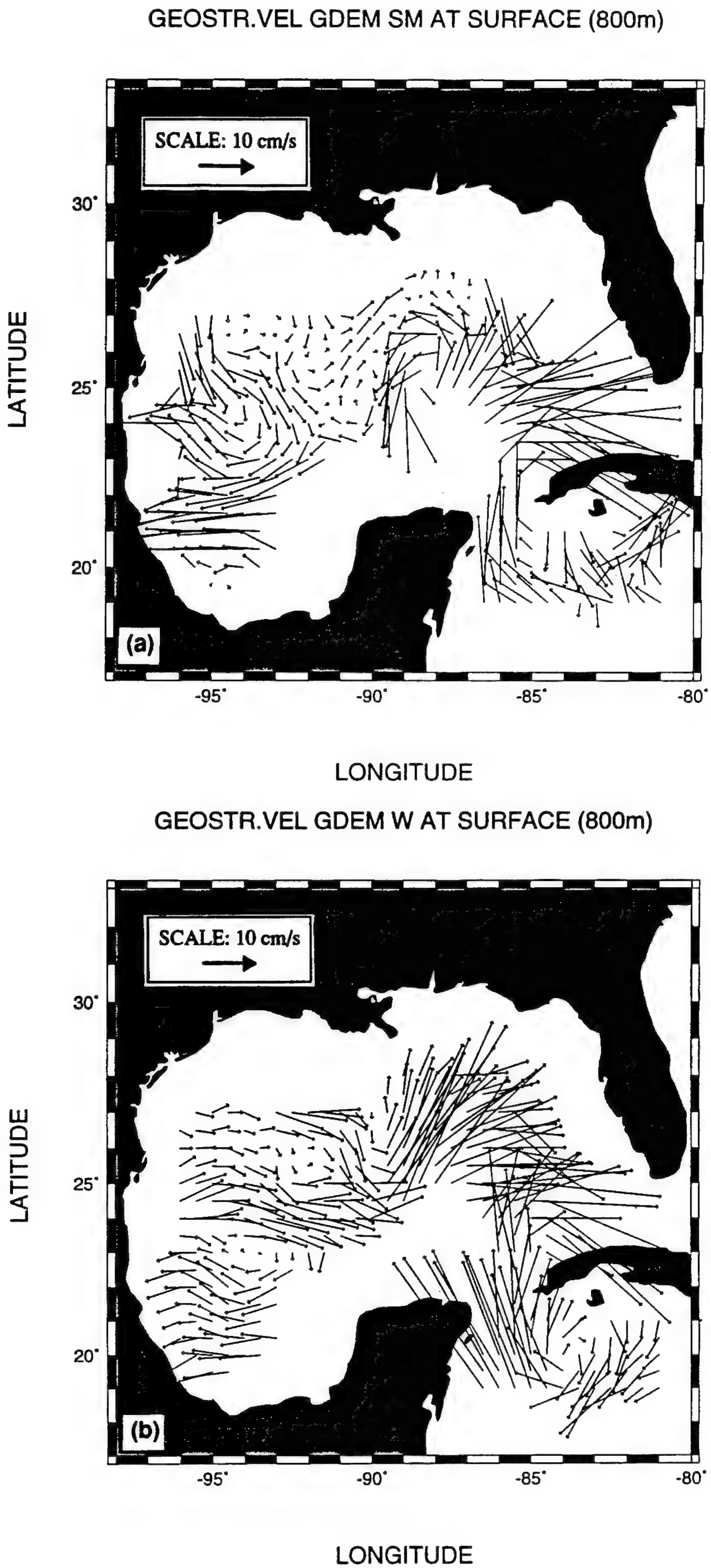


Figure 5.1.1-11. Surface geostrophic circulation 1/2°×1/2° in the Gulf of Mexico, (a) summer and (b) winter obtained from GDEM data. Reference level 800 m.

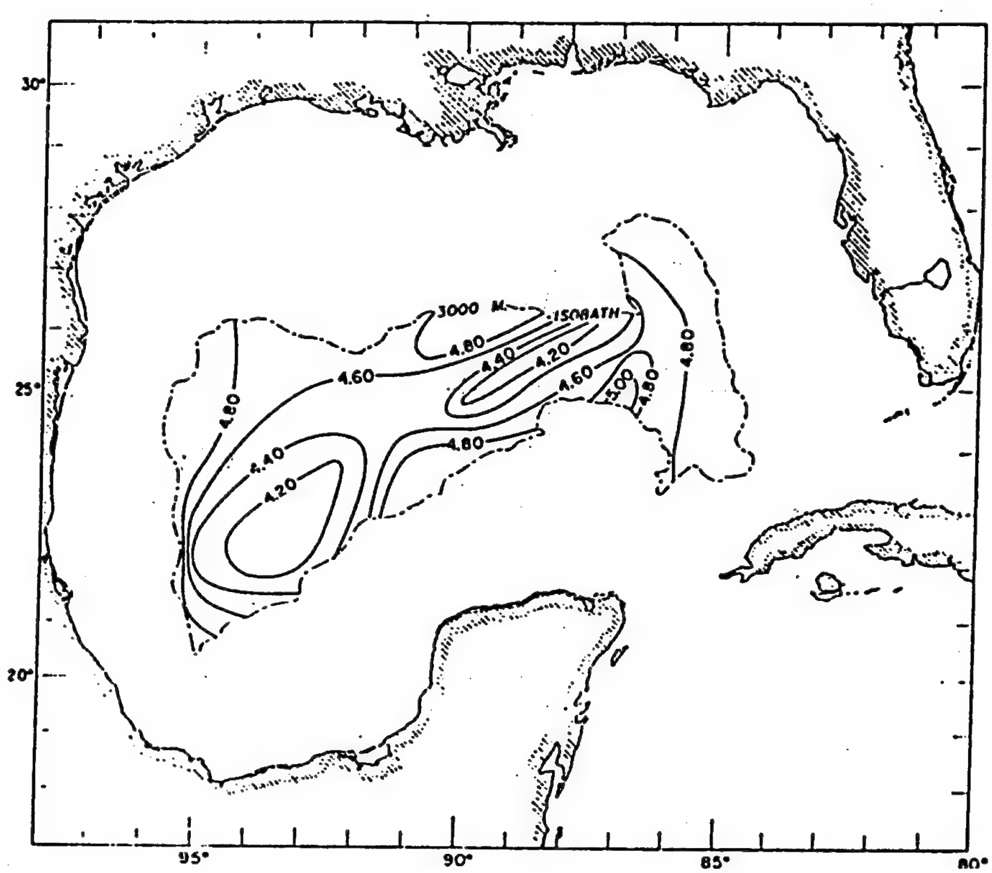


Figure 5.1.1-12. Contours of dissolved oxygen (ml/l) in the Gulf of Mexico at 3000 m. From McLellan and Nowlin (1963).

Worley (1986) found, using an inverse analysis method on CTD data, that the western rings extend to the bottom, and Nowlin and McLellan (1967) found variability in oxygen data at 1200 m which pointed to the deep extension of the rings. The level of abyssal kinetic energy in the north-central and the northwestern gulf is higher than the 1 cm^2/s^2 level of the "quiet" areas in the northwestern Atlantic.

(4) Gulf of Mexico, Implications About Waste Isolation

The Gulf of Mexico basin circulation is energetic, and there are few areas that are not influenced by the Loop Current and anticyclonic rings. The abyssal currents in the central-western gulf appear to be the weakest in the basin; however, the numbers and locations of observations have not been sufficient to estimate the occurrences of "abyssal storms" that could be caused by the passage of an eddy. Long-term arrays of current meter moorings are required to obtain reliable estimates about site locations for possible waste isolation sites. The residence time studies and oxygen distribution offer some evidence that vertical and horizontal mixing are relatively weak in the south-central-western basin areas, so isolation on a 100-year time scale may be feasible.

(5) Northwest Atlantic and Gulf of Mexico, Summary of Discussion Regarding Abyssal Flow

The northwestern Atlantic abyssal ocean is very active. It is involved in strong thermohaline circulation due to cooling and overturning of salty waters carried by the Gulf Stream to subarctic regions. Resulting southward-flowing cold water forms the Deep Western Boundary Current flowing against the continental margins of Canada and the eastern U.S. This strong abyssal current with the Gulf Stream and warm- and cold-core rings energize the abyssal environment and interact with the bottom. Resulting abyssal storms can erode sediments and cause its suspension. The nepheloid layer is present north of 35°N to the U.S. continental margins extending to 2000 m. The fine suspended particles with their high surface area could be important adsorbers, or sinks, of substances leached from deposited materials. In the area south of about 20°N the eddy kinetic energy increases, indicating that the abyssal environment is more energetic in the vicinity of the North Equatorial Current. The least energetic abyssal environment indicated by existing data and deduced from the review of literature is located west of the mid-Atlantic Ridge in the southern corner of the northwest Atlantic between 23°N to 30°N and 50°W to 65°W. Also, the surface currents and mesoscale eddy activity are low in this area, making it appear to be the most suitable for waste isolation from the standpoint of possible dynamical influences.

The Gulf of Mexico is geographically much smaller than the northwest Atlantic and abyssal depth reaches only to about 3500 m. The surface currents are strong in the eastern part of the gulf because of the Loop Current. The middle and western sections of the gulf are seeded by the westward-drifting anticyclonic rings, which resemble those in the northwest Atlantic. The high surface current speeds in the Loop Current and rings compromise the utility of these areas as good waste isolation sites. Abyssal currents in the eastern gulf are relatively strong and well correlated with the surface currents. Only one set of

measurements in abyssal depth at the north-central and the northwestern parts of the gulf indicated presence of topographic Rossby waves. In addition to these, the interaction of the rings with the seafloor and enhanced interactions between rings and slope in the western gulf during ring dissipation raises the eddy kinetic energy well above the northwest Atlantic minimum of 1 cm^2/s^2. Oceanographically, the most suitable locations in the Gulf of Mexico for waste isolation are in the south-central and southwestern parts of the gulf.

It is important to be aware of the scarcity of abyssal measurements. The near bottom enhancement of currents, existence of advected nepheloid layers, and the presence of enhanced radiated energy in locations selected as the "most suitable" isolation sites cannot be excluded. It is therefore necessary to investigate a chosen site with well instrumented moorings to obtain information about the near- and far-fields of the potential site.

(6) Northeast Pacific, Surface and Intermediate Flow Characteristics

The northeastern Pacific Ocean lies at the far end of the oceanic "conveyor belt," with deep waters which are "oldest" in the sense that it has been more than 500 years since they lay close to the ocean's surface. The flow regime is characterized as that of an eastern boundary region without the strong flows characteristic of the Gulf Stream or the associated mesoscale Gulf Stream rings. Deep and bottom waters are not formed in the region.

(a) Surface Circulation

Between 20°N and 50°N the North Pacific Current and the Subarctic Current advect surface waters from the west into the eastern North Pacific Ocean. As these flows approach the coast, they diverge, flowing equatorward and poleward, respectively, as the California Current and the Alaska Current. This pattern is evident in Figure 5.1.1-13 which represents the surface geostrophic velocity in the northeastern Pacific. This system is modified seasonally by surface weather systems. In late fall and winter, the Aleutian low dominates, with northeastward winds along the California coast interrupted by weekly storms, and the region of divergence between subarctic and subtropical gyres lies at about 40°N. During this winter period, the Davidson Inshore Current is found at the surface next to the coast, transporting water poleward. The Davidson Current is about 100 km wide. Strongest winter surface currents are associated with winter storms, and can be estimated as about 2% of the maximum sustained winds.

In summer the North Pacific high pressure system dominates the eastern North Pacific. The region of divergence between subpolar and subtropical gyres retreats poleward to about 50°N. This high-pressure distribution also provides steady southeastward winds along the California coast; this results in southward acceleration of the California Current, isopycnals increasing their upward slope toward the coast, upwelling at the coast, and disappearance of the Davidson Current. The upwelling does not occur uniformly along the coast, but is most intense at capes and headlands along the coast. Jets or squirts at these capes transport the upwelled water offshore into the ocean interior. The most prominent of these jets occurs at Pt. Reyes, transporting water that was upwelled along the southern Oregon and northern California coast offshore to about 127–128°W, where it turns southward, meandering

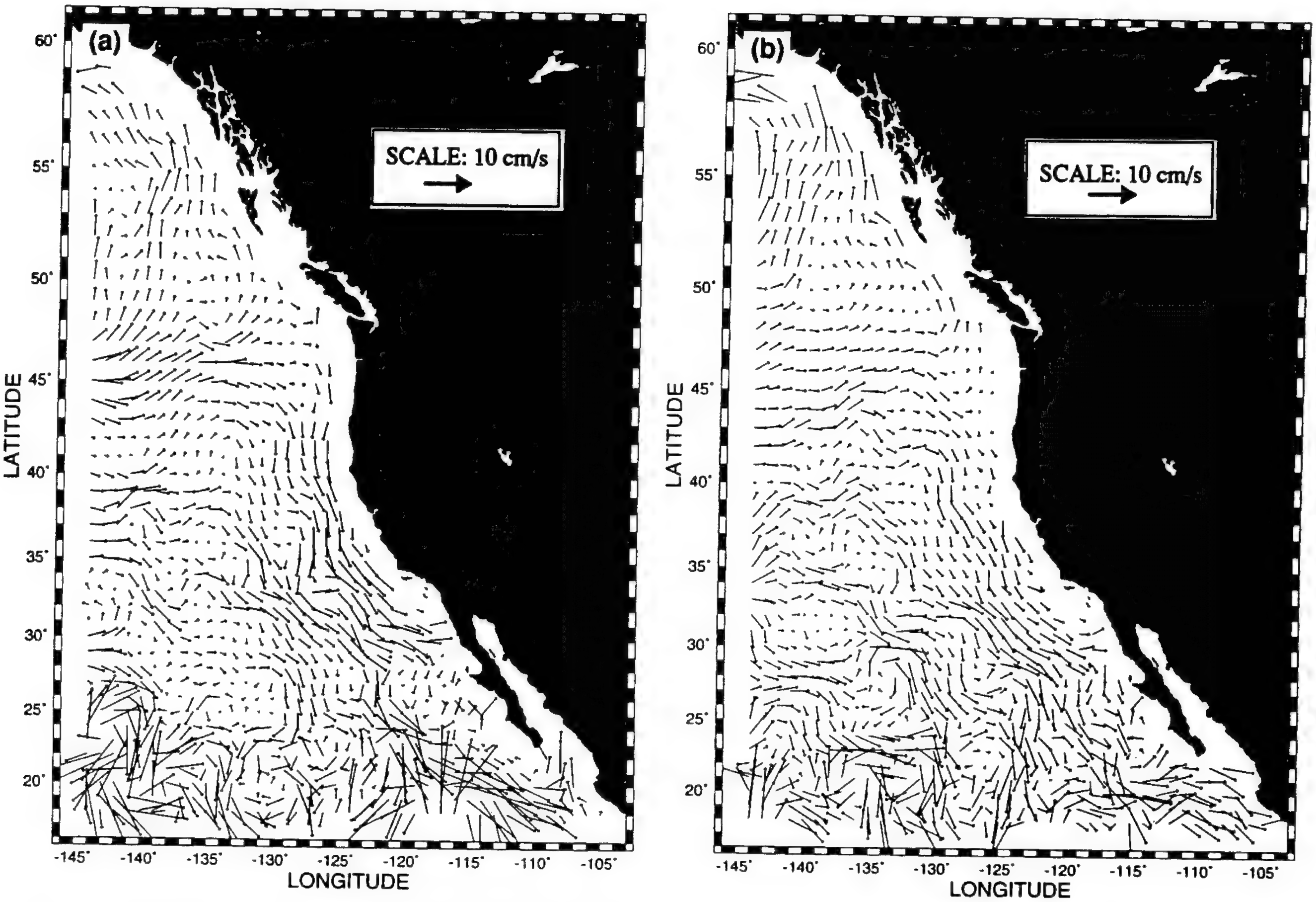


Figure 5.1.1-13. Surface geostrophic velocity 1°×1° in the Northeastern Pacific, (a) summer and (b) winter obtained from GDEM data. Reference level 1000 m.

along these meridians. Note that this boundary coincides with the region of maximum variance of water properties noted by Lynn and Simpson (1987) offshore the central California coast. Maximum surface velocities are associated with these jets or associated eddies and meanders and can exceed 1 kt.

In the region of the southern California bight, the surface circulation is dominated by the southern California eddy. The eddy brings surface waters from the west and south into the bight south of about 32°N, with part of the water turning northward to feed the Southern California Countercurrent, and part turning southward along the northern Baja coast. The Southern California Countercurrent flows northward along the coast in the southern California bight, and transports waters offshore to the south of Point Conception (Lynn and Simpson 1990). Although this pattern is evident in large-scale charts of dynamic topography (Wyllie 1966), direct measurements in July 1985 indicated that the onshore flow was confined to a 50 km wide filament of cold and low-salinity water (Niiler et al. 1989). The southern boundary of this eddy is marked by a persistent front.

As one proceeds along the great circle route from the west coast to Hawaii, three major frontal zones are encountered: the subarctic front (33.8 psu) (sometimes called the California front in this region (Saur 1980), the northern subtropical front, and the subtropical front (18°C, 34.8 psu), the latter marking the northern boundary of North Pacific Central Waters. These fronts lay in the region between 900 and 1400 km from the coast. They appear as surface outcroppings of haloclines: the subarctic halocline where salinity increases with depth and the subtropical halocline where the opposite prevails. The subpolar and subtropical fronts and the processes that control them have been described by Roden (1975, 1980) and Niiler and Reynolds (1984). The northern subtropical front has been described by Lynn (1986) and Roden (1975); it falls 200–300 km north of the subtropical front and has temperature salinity characteristics of 14–17°C and 34.4 to 34.6 psu. Lynn (1986) found narrow cores of extra-high salinity that indicated current jets at the high-salinity side of the northern subtropical front and, sometimes, the subarctic front. Lynn (1986) also found that these fronts were not always strongly developed and that they could be diffuse and broken.

(b) Intermediate Waters

Northwestern Pacific Intermediate Water (NPIW) is formed in the northwestern Pacific Ocean (Reid 1965) and transported into the northeastern Pacific Ocean by the North Pacific Current. These waters are associated with density anomalies of 26.6 to 26.7 kg/m^3 and are characterized as cool, fresh, and highly oxygenated. Along the west coast (from Baja California to Vancouver Island), the NPIW is displaced offshore by equatorial waters (warm, salty, low oxygen) which have been transported poleward by the California Undercurrent. The undercurrent usually occurs within 100 km of the coast, has a transport of less than 5 Sv, and has a velocity maximum of less than 1 kt that occurs at depths between 100 and 300 m.

(c) Oxygen Minimum Layer

An oxygen minimum layer occurs beneath the NPIW in the northeastern and eastern tropical Pacific Ocean (where it is associated with Antarctic Intermediate Water). Between depths of about 750–850 m, oxygen of less than 10 μmol/kg (about 3% of saturation) are found, but at abyssal depths, oxygen values are quite high, approaching 150 μmol/kg (about 43% of saturation) at 5000-m depth.

(7) Northwest Pacific Deep and Bottom Waters

(a) Circulation

Johnson and Toole (1993), Reid (1981), Mantyla and Reid (1983), and Reid and Mantyla (1978) have used water mass properties, steric heights, and geostrophic shear to infer the circulation of deep and bottom waters in the North Pacific. Deep waters are characterized by a maximum in silicate, and bottom waters by an increase in oxygen and decrease in silicate. Johnson and Toole (1993) used a potential temperature $\theta = 1.2°C$ to separate deep and bottom waters and $\theta = 2.0°C$ to separate deep and intermediate water. The flow patterns for these waters differ from those for intermediate and surface waters. Reid and Mantyla (1978) suggest that deep waters flow from the west toward coast of southern California near 20–30°N, move poleward along the coast, and then flow to the west off the coast of Oregon, forming an anticyclonic gyre near 40–50°N, which is centered south of the Aleutian Islands.

The bulk of the Pacific Deep Water flows northward along the western side of the south Pacific Ocean along the boundary formed by New Zealand and the Tonga-Kermadec Trench. Reid et al. (1968) examined a detailed section along 28°S and found the deep-boundary current to be 100 km wide, confined to depths between 2500 and 4500 m, and he estimated volume transport as 8 to 12 Sv. These waters can be traced north through the Samoan Passage which separates the deep basins of the north and south Pacific (Warren 1981). These waters subsequently appear to flow northeastward to the east of Hawaii at depths greater than 4500 m, as well as northeastward to the east of the Marinas. Johnson and Toole (1993) suggest that between 24°N and the equator, the bottom water is moving south along the western flank of the East Pacific Rise (150°W–120°W).

Deep and bottom water properties are remarkably uniform (Levitus and Boyer 1994; Levitus et al. 1994). Table 5.1.1-3 provides estimates of these properties for abyssal waters adjacent to the continental U.S. Standard errors include both measurement errors and geographical variability. For deep water, the contributions to stability from changes of in situ density are nearly balanced by the effects due to the compressibility of seawater, $-gC^{-2} \approx -400 \times 10^{-8} m^{-1}$, and stability is close to being neutral, i.e. $E \approx 0\ m^{-1}$.

(b) Velocities

The earliest deep-current measurements in the eastern North Pacific (Isaacs et al. 1966) were of relatively short duration (less than 4 days) but used speed rotors of a special design

that had a very low static friction, allowing rotation at speeds of about 0.56 cm/s and with stall speed of 0.44 cm/s (Schick et al. 1968). With time, deployment periods have increased (and now exceed two years), but most instruments have had speed sensors with starting thresholds that exceeded 2 cm/s (see, for example, Taft et al. 1981). Results of measurements made prior to 1978 in the eastern Pacific have been summarized by Wilcox (1978). He concluded that typical mean current speeds varied from 2 to 10 cm/s with maximum speeds ranging from 5 to 25 cm/s, but the smallest mean and maximum current speeds were recorded between 20°N and 40°N. He suggested a 10 cm/s operational current and a 25 cm/s survival current, but also noted that the existing database was marginal for purposes of providing useful guidance for the design of deep-ocean equipment. These current measurements fail to indicate a consistent pattern for deep-ocean flow; they do contain tidal periodicities that often dominate the variability of the records.

Subsequent to 1980, additional long-term measurements were made in the area of interest (Stabeno and Smith 1987) as well as in areas that are adjacent to the primary area of interest (Warren and Owens 1985; Hu and Niiler 1987; Cummins and Freeland 1993; Royer 1994; Noble and Kinoshita 1992). Measurements reported by Stabeno and Smith were collected in a relative flat basin 100 to 400 km off the northern California coast between the Mendocino Fracture Zone and the Pioneer Fracture Zone in water depths ranging between 3400 and 4400 m and included measurements within 500 m of the bottom. At one location (39–27.7°N, 127–41.8°W) they were successful in obtaining a 5-year record for currents at 3800 m. They found that the behavior of the deep currents shoreward of the 4000-m isobath differed markedly from those seaward. Deep currents near the slope appear as if bandpassed, with much of the very-low-frequency energy filtered from the currents. Farther offshore, although mean currents were less than 1 cm/s (see Table 5.1.1-4), the records were dominated by energetic low-frequency variability in the 31- to 120-day band with a kinetic energy per unit mass of 2.0 cm^2/s^2.

We provide two examples of the character of deep flow. The first is from the current measurement program sponsored by the Department of Energy (Stabeno and Smith 1987) described briefly above. We have used current measurements for a depth of 4300 m, about 40 m above the bottom, but to assemble a continuous record it was necessary to include 3800-m current measurements for the period 22 September 1982–2 September 1983. This can be justified by the high coherence (0.88) between 3800 m and 4300 m reported by Stabeno and Smith (1987). For consistency, we also vector-averaged the half-hourly measurements obtained for the period 13 March–29 August 1981 so that the entire series consisted of hourly data. The maximum recorded speed was 15 cm/s, the average speed was 3.7 cm/s, and the standard deviation of the speed was 2.5 cm/s. The speed histogram has modes at 1 and 4 cm/s, with the former representing about 27% of the observations. The direction histogram has modes at 170° (about 11% of the observations) and at 330°; since these directions are nearly reciprocal to one another, the modes are likely due to topographic steering, although the flow is not as severely constrained as those observed on the shelf and slope.

Table 5.1.1-4 contains cumulative statistics which correspond to the right-hand tail of the velocity histogram. Observations that exceed the specified speed are counted and listed in the second column. When contiguous samples exceed the specified speed, they are

Table 5.1.1-3. Physical and Chemical Characteristics of the deep NE Pacific Ocean adjacent to the continental United States

parameter	3000 m	4000 m	5000 m	std. error
θ, ^{0}C	1.360	1.160	1.125	0.011
salinity, psu	34.662	34.682	34.687	0.001
DO_2, µM / kg	111	140	150	2
NO_3, µM / kg	38.8	36.9	36.2	0.2
PO_4, µM / kg	2.75	2.57	2.52	0.02
SiO_3, µM / kg	176	167	159	1
γ_4, kg / m^3	45.810	45.863	45.874	0.003
E, 10^{-8}m^{-1}	7.1	2.3	.5	0.3

Table 5.1.1-4. Bottom current observations which exceed a given value of hourly speed at 39-27.7°N, 127-41.8°W during the period August 1979 to September 1984.

Speed, cm/s	No. of Hourly Observations	No. of Separate Events	Mean Time Between Events, Days	Max Duration, Hours
10	543	247	7.3	7
11	244	113	14.6	7
12	96	49	34.1	7
13	39	22	77.5	4
14	12	7	238	2
15	1	1	not observed	1

grouped as one event, and these events are summed in the third column. The mean time between events is given in the fourth column, and the maximum duration of the event is given in the last column. Statistical methods (Gumbel 1958) can be used with these data to project extreme events. For example, the maximum current speed expected in a 100-year period is estimated to be 17 cm/s. Note however that this mooring did not exhibit the type of behavior reported by Freeland (1993) where the low-frequency variability at 3000 m of 1–2 cm/s was dominated by a 50-day pulse of southward flow which exceeded 10 cm/s.

The second deep-velocity time series that we present was collected 7 m above the bottom at 33–30°N, 122–03°W where the water depth is 3910 m. These data were collected as part of the CalCOFI program; the data record spans 155 days, from 14 April–7 August 1972 and consists of hourly observations. Figure 5.1.1-14(a) shows the time series and Figure 5.1.1-14(b) the speed histogram. The mean speed was 2.9 cm/s, the standard deviation 1.7 cm/s, and the maximum observed speed 10.4 cm/s. The most frequently observed speed was 2 cm/s, accounting for 26% of the observations. The character of the time series and speed histogram is markedly different at low speeds from that obtained during the DOE measurements, due to the lower threshold of the speed rotor (Schick et al. 1968), and therefore better represents the distribution of near-zero speeds. Although speeds seem less than those observed at the DOE site, note that it is possible to find 155-day segments in the DOE record with a similar speed maximum. The flow directions are highly variable without a well-defined mode; westward flows were most frequently observed (7%), while flows directly toward the coast (050°) were observed about half as often.

The progressive vector is given for one current meter deployment described in Figure 5.1.1-15. The progressive vector, $V(t)$, begins at the origin and follows the path obtained by summing the observed velocity, $v(t)$, with time, t,

$$V(t) = \int_0 v(t)dt.$$

The difference in scales is due to the fact that the DOE measurements are summed over 5 years while the CalCOFI measurements are summed over 5 months. Note that even small velocities are capable of transporting material great distances. Year-to-year differences in the deep-velocity field are evident, and although the flow is persistently southeastward, there are periods of time (such as 1983) when the flow is in a different direction. The CalCOFI data show that the direction of the flow can vary over weekly and monthly periods, from northeastward at the beginning of the record, to southward, and northward. The CalCOFI data, because of the larger scale, also clearly show tidal variability that is noted in all abyssal current measurements in the northeastern Pacific Ocean.

Table 5.1.1-5 summarizes the characteristics of deep (3000 m or greater) Eulerian flow measurements for the eastern portion of the northeastern Pacific Ocean that were not included in Wilcox (1978). Away from boundaries, mean speeds are generally about 5 cm/s and the maximum observed speed was 25 cm/s. The pattern of mean flow appears highly chaotic and does not reflect the pattern of flow of bottom waters deduced from water properties.

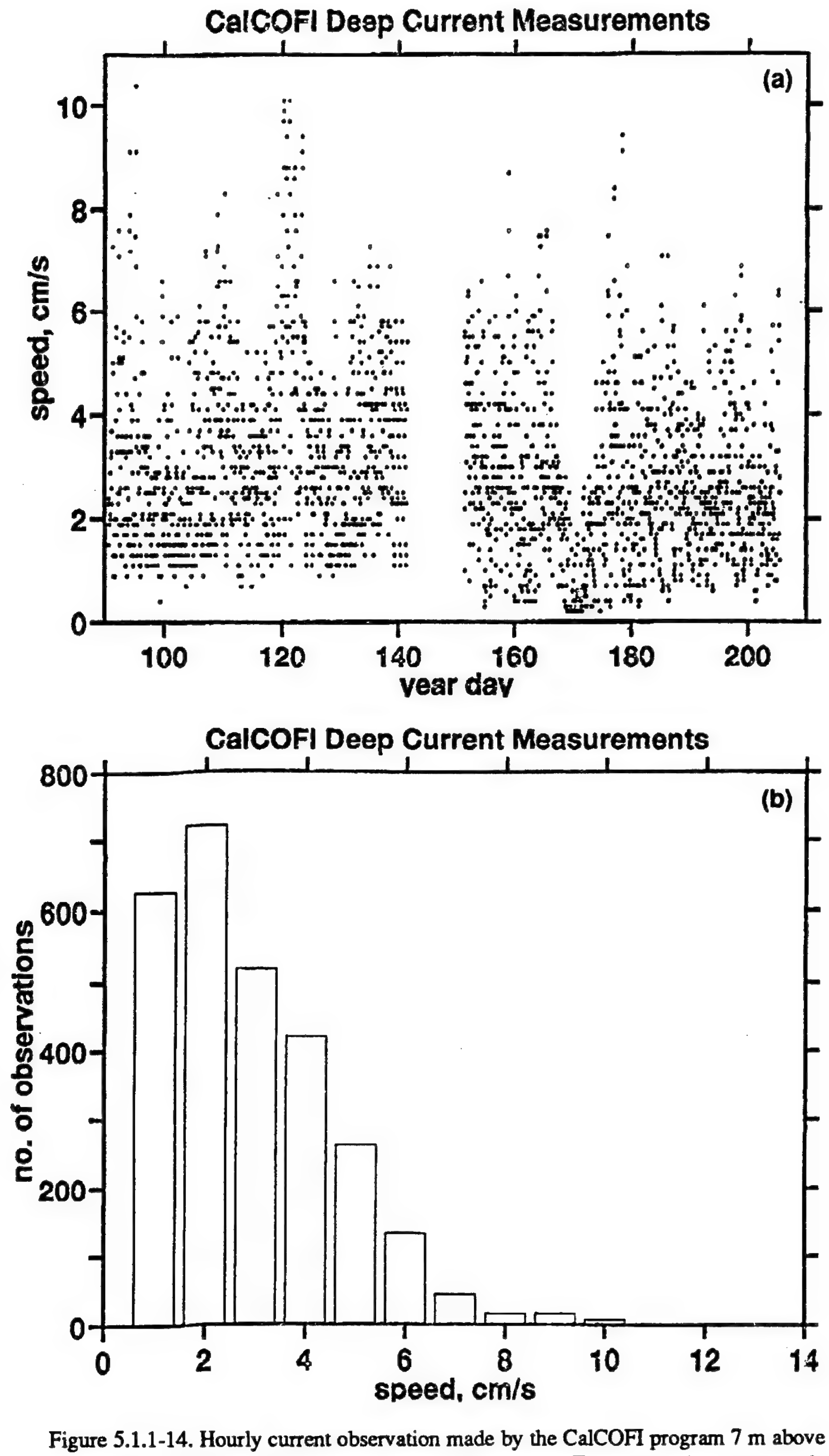


Figure 5.1.1-14. Hourly current observation made by the CalCOFI program 7 m above the bottom at 33.5°N, 122°W in water that is 3900 m deep. The observations were made between 14 March and 7 August, 1972: (a) speed and (b) histogram of hourly speed.

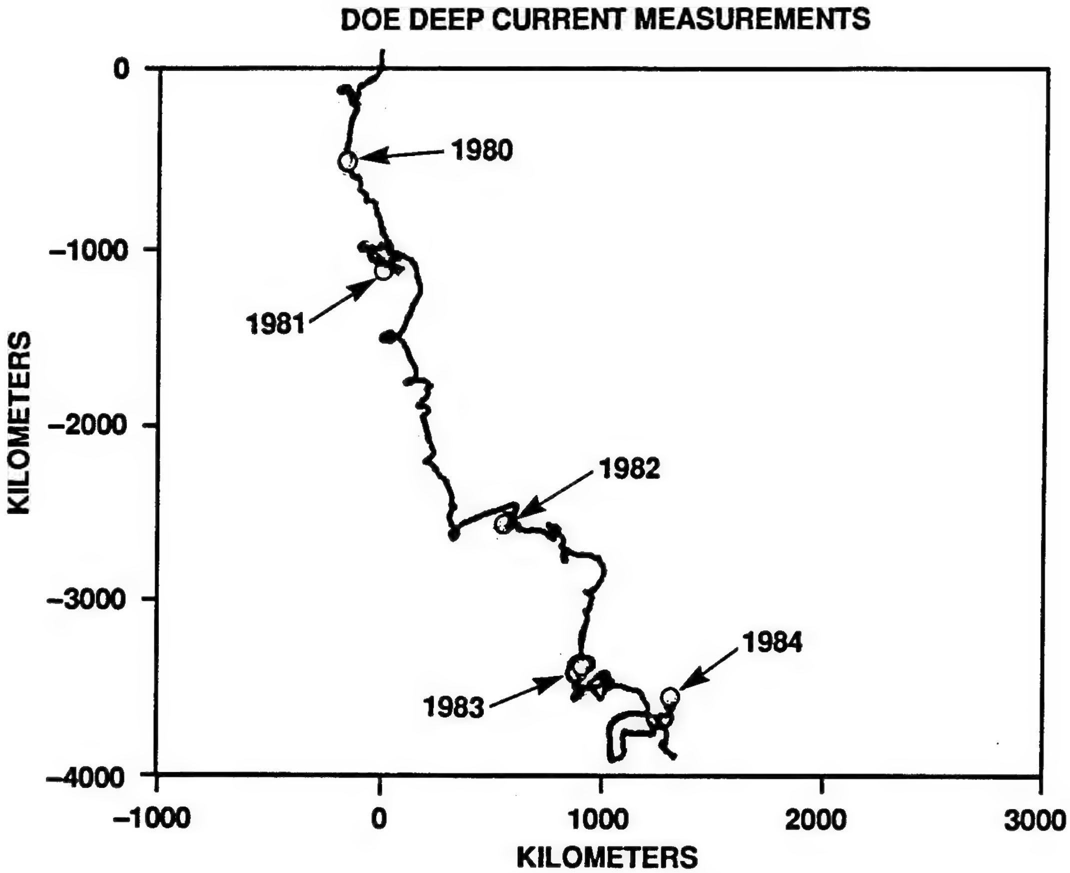


Figure 5.1.1-15. Progressive vector diagram for hourly current observations at 4200 m depth at 39.5°N, 127.7°W from 13 August 1979 to 27 September 1984. These observations were made by Oregon State University as part of a Department of Energy investigation of possible disposal sites for nuclear powered submarines. The circles represent the beginning of year (the first is 1980 and the last is 1984). From Health et al. (1984).

Table 5.1.1-5. Selected statistics for recent long-term abyssal current measurements in the Northeastern Pacific Ocean.

Latitude	Longitude	Depth	Start	End	dt	Experiment	$\overline{S}$	S	$\overline{u}$	$\overline{v}$	Direction
N	W	m			min		$cm\ s^{-1}$	$cm\ s^{-1}$	$cm\ s^{-1}$	$cm\ s^{-1}$	°T
33.5	-122.0	3899	Apr-72	Aug-72	60	CalCOFI	2.9	17.9	-0.3	0.3	315
38.2	-124.4	3355	Sep-84	Jul-85	60	OPTOMA	3.4	11.7	0.0	-0.4	177
38.2	-125.6	3810	Sep-84	Mar-85	60	OPTOMA	4.5	16.1	-0.2	0.2	323
38.6	-126.4	4210	Sep-81	Sep-82	60	LLWODP	5.3	21.7	3.4	4.9	169
38.9	-125.0	3250	Sep-84	Jul-85	60	OPTOMA	3.9	14.3	2.4	3.6	35
39.1	-127.4	4310	Jun-80	Sep-82	60	LLWODP	6.3	19.7	-1.6	-4.3	201
39.5	-127.7	4200	Aug-79	Sep-84	60	LLWODP	3.7	15.0	0.3	-0.6	155
39.5	-128.8	4200	Aug-81	Sep-82	60	LLWODP	5.5	14.1	4.0	1.9	65
39.5	-126.8	4140	Sep-81	Sep-82	60	LLWODP	6.1	24.7	-1.1	-1.3	220
57.3	-148.5	4900	Nov-86	May-87	30	UAlaska	8.2	35.4	-0.6	-2.5	195

(c) Lagrangian Characteristics

Although current meter data provide information on the current speeds, directions, and kinetic energy levels, Lagrangian path and dispersion are keys to understanding the fate of wastes that are dumped in the ocean. There have been no extended subsurface float measurements in the northeastern Pacific Ocean. To our knowledge, there has been only one experiment in the Pacific which measured dispersion below the main thermocline. This experiment was conducted by Ewart and Bendiner (1981). They twice injected a 25-m × 5-m × 2-m thick patch of Rhodamine B dye at 1000-m depth at 30–08°N, 124–25°W and measured the dispersion of these patches over a period of 42 hr. They obtained dispersion rates of 360 cm^2s^{-1} for horizontal space scales less than 200 m.

Dispersion can also be estimated from particle-pair separation statistics (Davis 1985). For surface waters, drifting buoys have been used to estimate particle-pair dispersion. These drifting buoys are drogued so as to be tightly coupled to water motion and with minimum above-water exposure to winds. Davis (1985) estimated dispersion from releases of drifters in a coastal upwelling region off northern California. He found dispersion depended on both time and initial separation distance in a manner that was not well described by scale-dependent diffusivity; largest dispersion occurred for separations greater than 30 km and was 10^7 cm^2/s; their meridional statistics suggest a 4/3 power law behavior.

In the northeast Atlantic (an eastern boundary region, but the deep circulation is believed to be considerably more vigorous than the North Pacific), subsurface particle-pair dispersion has been estimated using SOFAR floats (Ollitrault 1994). Fourteen SOFAR floats were launched at depths between 3700 and 4100 m near 47°N, 20°W for a period of one year. These floats dispersed over an area of about 300 km diameter. Individual trajectories revealed small-scale structures associated with the underlying topography, with occasional rapid bursts to 10 cm/s over distances of a few kilometers. The Lagrangian time scale was about 6 days and the equivalent horizontal turbulent diffusivity was 5×10^6 cm^2 /s. (This contrasts with surface ocean diffusivities of $3\times10^4 cm^2/s$ measured with tracers (see Ledwell et al. 1993)). Ollitrault attributes float dispersion solely to topographic interaction. Mean currents were of the order of a few mm/s, while eddy kinetic energy per unit mass was of order 10 cm^2/s^2.

(8) Northeastern Pacific Summary of Discussion Regarding Abyssal Flows

In terms of extreme accelerations and rapid changes of water properties, the abyssal circulation of the northeastern Pacific Ocean is benign. Away from boundaries, mean speeds are generally about 5 cm/s and the maximum observed speed was 25 cm/s. Since neither deep nor bottom water is formed in the region, water properties are remarkably uniform and highly oxygenated. Dispersion rates are likely to vary from 10^2 cm^2/s for 100-m scales to 10^6 cm^2/s for 100-km scales. Since the stability of bottom waters is very close to neutral, care must be exercised regarding the introduction of buoyant material at these depths.

5.1.2 Physical Oceanographic Modeling *by Patrick C. Gallacher*

At our current levels of understanding and technology, numerical models can simulate our physical environment with a sufficient degree of accuracy to aid in interpreting data, to augment existing datasets, to assist in experimental design, and to provide fundamental understanding of the important physical processes that govern the mean and turbulent flows in the ocean. Observations of the ocean are sparse in both space and time, especially in the deep ocean, so it is our intent to elucidate the physical processes that affect the possible dispersion of contaminants from isolation sites using numerical models. These processes also impact the selection of potential locations for isolation sites and were included in the site selection criteria (see Section 3.3, **Site Selection Model**).

To understand the impact and dispersion of waste products we need to consider a very large group of physical, biological, chemical, and geological processes over a very wide range of temporal and spatial scales. In this section we will consider only the physical processes, and even with this limitation, the range of scales requires the use of several distinctly different models. We will discuss ocean-circulation models that encompass entire ocean basins, mesoscale models that cover a domain of roughly 100 square kilometers around the isolation site, and submesoscale models that examine the dynamics of the plumes of effluent escaping from bags at the isolation site over areas of less than 1 km.

Since the local velocity field results from both local and remote forcing and from basin scale constraints on the circulation, the entire basin must be modeled for this part of the study. The ocean-current velocity is an important site selection criteria. It is also needed to assess the potential for large-scale dispersal of contaminants. Furthermore, the velocity field is needed to provide boundary conditions for the mesoscale and submesoscale models.

The degree of dispersion of contaminants from an isolation site will be strongly influenced by submesoscale to mesoscale ambient dynamics at the site in addition to the dynamics of any plumes of water and material that originate at the site. The submesoscale to mesoscale encompasses scales less than 1 km to 100 km. Any dispersion of the waste-associated material is likely to contaminate at least an area of approximately mesoscale proportions in the vicinity of the site. However, we cannot address the potential effects on these scales until both the large-scale flow field, the near-field processes, and rates of introduction of the contaminants into the deep-ocean system are better known. Thus the submesoscale and mesoscale modeling will be addressed last.

To accurately assess the potential for contamination of the abyssal ocean we must determine the amount of waste material that might leak from a bag (or bags) and its chemical and physical composition. For example, we need to know the solubility, particle size distribution, settling velocities, and cohesiveness of the material. We must also understand how the waste will interact with the environment. The waste material and pore water will form a buoyant plume that may rise as much as 200 m in the neutrally buoyant abyssal waters and we need to determine how long the contaminants will stay suspended or dissolved in the water. Small particles may be given significant upward velocity by the convectively driven turbulence in the plume, and the settling velocities of these particles, if they don't

agglomerate, can be quite small. In Section 5.1.1, **Physical Oceanographic Measurements,** it is estimated that particles in the 1 to 10 μm size range may have residence times of one month to two years based on their settling velocity alone. Below, we describe an initial simulation using a highly parameterized model designed for shallow-water dumping of loose dredged material at the ocean's surface. The simulation shows that the residence time may be much shorter if the particles aggregate. This is only a first approximation. Future simulations will be done using a sophisticated, high-resolution, nonhydrostatic model.

5.1.2.1 Description of Models

(1) Basin Scale Model

The basin scale model used in this study is a six-layer, finite depth version of NRL's multilayer ocean model. It is a primitive equation representation of a Boussinesq, hydrostatic ocean with a free surface. The equations are solved in spherical coordinates in a layer-averaged framework that allows momentum, but not density, to mix between layers. The model is similar to the hydrodynamical model described by Hurlburt and Thompson (1980), but it has been substantially augmented by Wallcraft (1991). Those changes include an interlayer mixing of momentum that is similar to McCreary and Kundu (1988) as it depends on the layer thickness. The velocity in each active layer thus varies horizontally and temporally as a result of horizontal advection and diffusion, vertical mixing due to entrainment and detrainment, and surface momentum fluxes based on the Hellerman and Rosenstein (1983) monthly wind climatology.

The model includes several passive tracers (i.e., they do not affect either the circulation or the density fields and there are no interactions among the tracers). These tracer equations have been used in the studies by Young and Kindle (1994), Bruce et al. (1994), and Gallacher and Rochford (in press), but the decay terms and the source regions for the tracers were different in each study, as appropriate to the phenomenon under investigation. The advection, diffusion, and interlayer mixing of the tracer are identical to that for momentum. In this study the tracers are used to visualize the dispersion of water parcels that are advected and diffused from the surrogate disposal sites. In this way we can determine the strength of the large-scale flow or the large-scale eddy kinetic energy that could advect or diffuse waste residue from an isolation site.

Two sets of basin scale experiments were used in this study, one for the North Atlantic and Gulf of Mexico and another for the North Pacific. Although the domains of the basin scale models are substantially larger than the study areas, the entire domain needs to be modeled to determine the density and velocity distributions that result from large-scale local and remote forcing. These fields are needed to select sites in low mean flow and low eddy kinetic energy regions and to provide boundary conditions and forcing functions for smaller scale regional and local models. These basin scale experiments require substantial supercomputer resources: to simulate one year, the North Atlantic–Gulf of Mexico model requires approximately 5 cpu (central processor unit) hours and 15 Mw (15,000,000 words) of memory, depending on the number of tracers included. The Pacific model domain is 1.5 times larger than the North Atlantic model. The North Atlantic Basin model domain

extends from 20°S to 65°N and from 99°W to 14°E. Thus the Gulf of Mexico and the Caribbean Sea are included (Fig. 5.1.2-1). The lateral boundaries are contiguous with the 200-m isobath and the boundary condition is no-flow at the walls. The locations and the magnitudes of the flow through the southern and northern boundaries are specified. This condition closes thermohaline circulation. Realistic topography is used with a no-flow bottom boundary condition. The surface boundary condition is a free surface where the surface wind stress is specified. The North Pacific Basin model domain extends from 20°S to 62°N and from 109°E to 77°W (Fig. 5.1.2-2). The lateral, surface, and bottom boundary conditions are the same as for the North Atlantic model.

(2) Plume Model

As a first attempt to determine the local effects associated with the impact, and possible rupture, of the bags containing waste (see Section 1.4.1, **Engineering Concepts**), we used a version of the STFATE model. The STFATE, Short Term FATE, model was developed at the Corps of Engineers Waterways Experimental Station (WES) (Johnson 1990) to evaluate the impact of the dumping of dredged material on the ambient water quality. The model parameterizes the descent, mixing, and dispersion of the dredged material in three stages: the convective descent phase, the dynamic collapse at the neutral buoyancy level or on the bottom, and the long-term passive spreading. The STFATE model assumes dredged material dumped from a hopper barge or a split hull barge at the surface in relatively shallow water. The waste stream consists of waste water of a specified temperature and salinity with several dissolved contaminants and particulates. The dump can be in several stages with the barge stationary or moving. The background water temperature, salinity, and velocity can be specified along with the background levels of contaminants. The model relies heavily on parameterizations of the physical processes involved in the dispersion of the dredged material; thus its applicability to the remarkably different environment of the abyssal ocean is questionable. We use it here largely to obtain a rough approximation of the residence times of particulates and dissolved chemicals that might be introduced into the water column by a ruptured or broken bag.

5.1.2.2 Results

(1) Basin Scale Model

Both the North Atlantic and the North Pacific Basin models were forced with the Hellerman-Rosenstein monthly climatological winds. The numerical experiments were initialized with layer thickness and velocity fields that were in statistical equilibrium, then the numerical experiments were integrated forward in time, 11 years for the Pacific model and 9 years for the Atlantic model. The mean currents for the last 3 years of the experiments were computed and eddy kinetic energy, the square of the standard deviations from this mean, was also computed. The mean currents determine the regions of strong and weak advection and the eddy kinetic energy defines regions of high and low diffusion, that, is the mixing and spreading that results from the large-scale turbulence, the temporal fluctuations

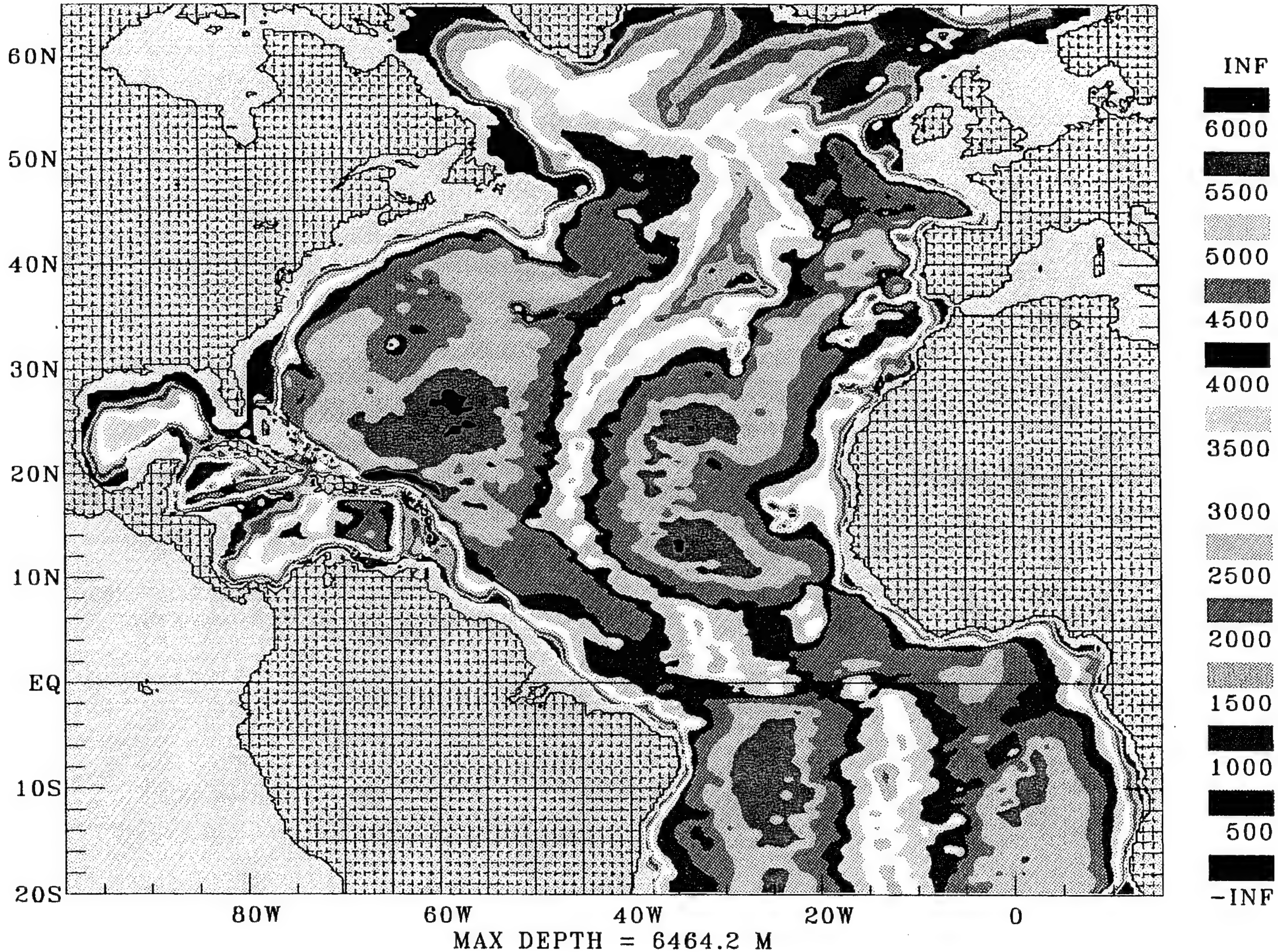


Figure 5.1.2-1. The Atlantic model domain showing the topography in meters. The cross-hatched region is land and the solid beige areas are water with depths less than 200 m, hence they are excluded from model calculations.

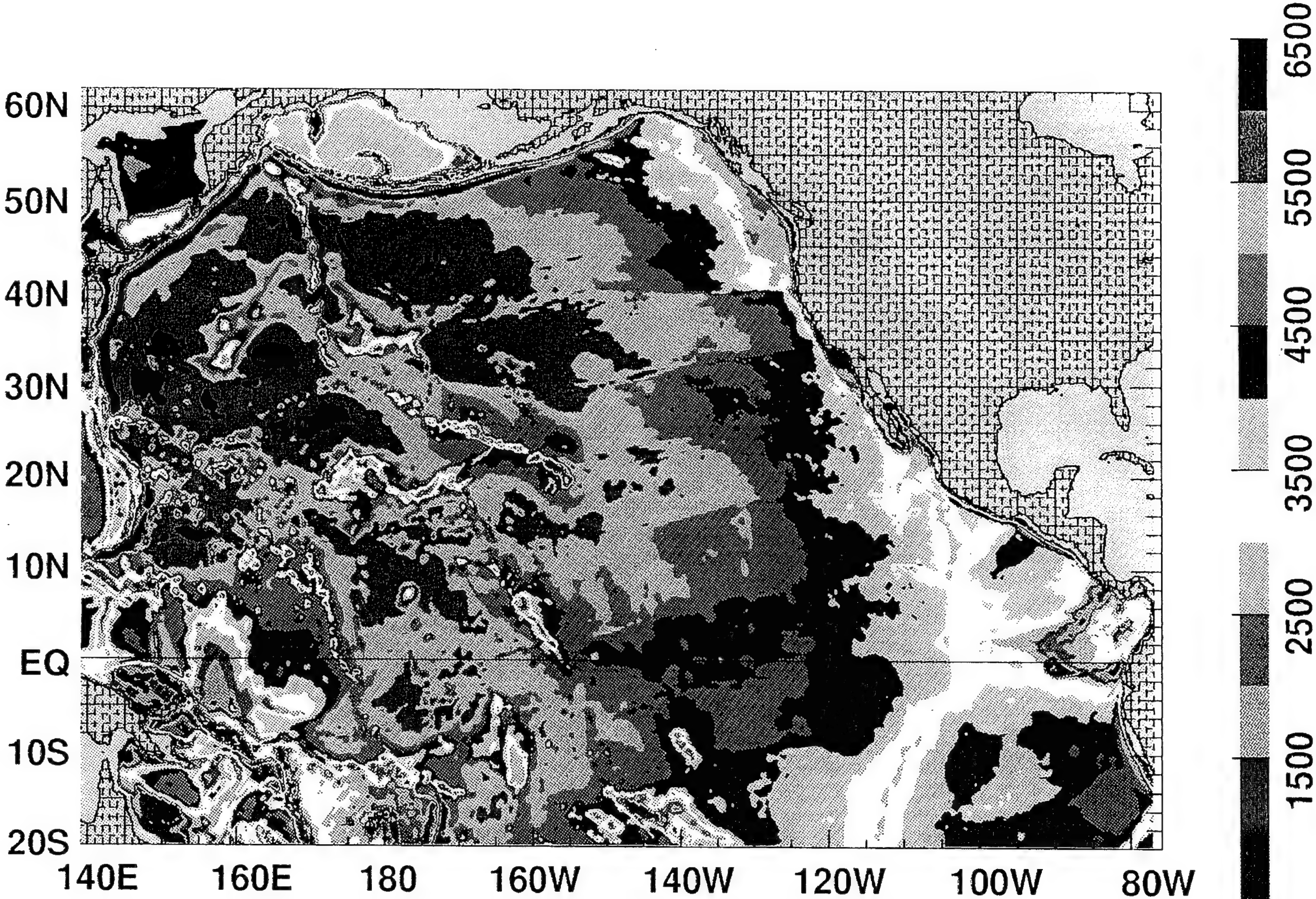


Figure 5.1.2.-2. The Pacific model domain showing the topography in meters. The cross-hatched region is land and the solid beige areas are water with depths less than 200 m, hence they are excluded from model calculations.

of the large-scale flow. We will focus on the results in the sixth, or bottom, layer. In these experiments the bottom layer is quite thick. This allows us to optimize the description of the circulation in the upper ocean which, along with topography, drives the flow in the lower layers. In both models the interface between the fifth and sixth layers is initially 1000 m. Thus the sixth layer includes all depths from approximately 1000 m to the bottom.

In the North Atlantic the mean currents in the bottom layer (shown as arrows in Fig. 5.1.2-3) and the kinetic energy of the mean flow (shown as color contours in Fig. 5.1.2-3) compare quite well with the best estimates based on a summary of all available measurements (see Fig. 5.1.2-4) (from Schmitz and McCartney (1993), Figure 12). The deep western undercurrent, which parallels the coast from 45°N to 34°N, is well represented; however, the recirculation southwest of the undercurrent is elongated in the north-south direction relative to the estimates of Schmitz and McCartney. This is probably due to the fact that the Gulf Stream separates from the coast further north in this version of the model than is observed. The eastern branch of the deep circulation that flows past Bermuda and reconnects with the undercurrent at approximately 35°N and the northern portion of the recirculation northeast of the Bahamas-Antilles Arc in the model agree with the description of Schmitz and McCartney. This agreement between simulated and measured flow means that we can adequately represent the effects of advection.

The spatial pattern of eddy kinetic energy in the North Atlantic experiment (Fig. 5.1.2-5) agrees well with observations (see Fig. 5.1.2-6) (from Thompson and Schmitz (1989), Fig. 1b). In Figures 5.1.2-3 and 5.1.2-5, the kinetic energy is plotted using a logarithmic scale, the conversion from logarithmic to geophysical units is given in Table 5.1.2-1. Areas with high energy levels are associated with the deep western boundary current off the coast of North America and with the Gulf Stream and the southern recirculation of the subtropical gyre.

Comparing Figures 5.1.2-5 and 5.1.2-6 we see similarities between the simulated and observed eddy kinetic energy. The tongue of high energy extending east-northeast from the coast at roughly 35°N agrees with the high energy band in Thompson and Schmitz; however, the simulated values are roughly 100 times smaller than the data and do not extend as far to the east. This is a result of problems with the Gulf Stream in this version of the model. These problems are known and will be corrected in future versions of the model. Although the relative magnitude of the eddy kinetic energy is incorrect, the location of the maximums is consistent with the observations. The tongue of high energy directed east-northeast from 40°N and the band of high energy extending eastward from 30°N also agree with the observations in position but are weaker.

In the Gulf of Mexico, the mean currents show the deep countercurrents associated with the Loop Current at the surface (Fig. 5.1.2-7). The mean current enters through the Straits of Florida and travels cyclonically (anticlockwise) around the gulf exiting through the Yucatan Straits. There is a recirculation in the western gulf and several smaller eddy-like structures in the eastern gulf. These features are associated with eddies shed from the Loop Current. The eddy kinetic energy is strongest in the region of eddy shedding in the eastern gulf, but it is also large over the abyssal plain in the western central gulf (Fig. 5.1.2-8). This is in agreement with the pattern of eddy kinetic energy seen in deep

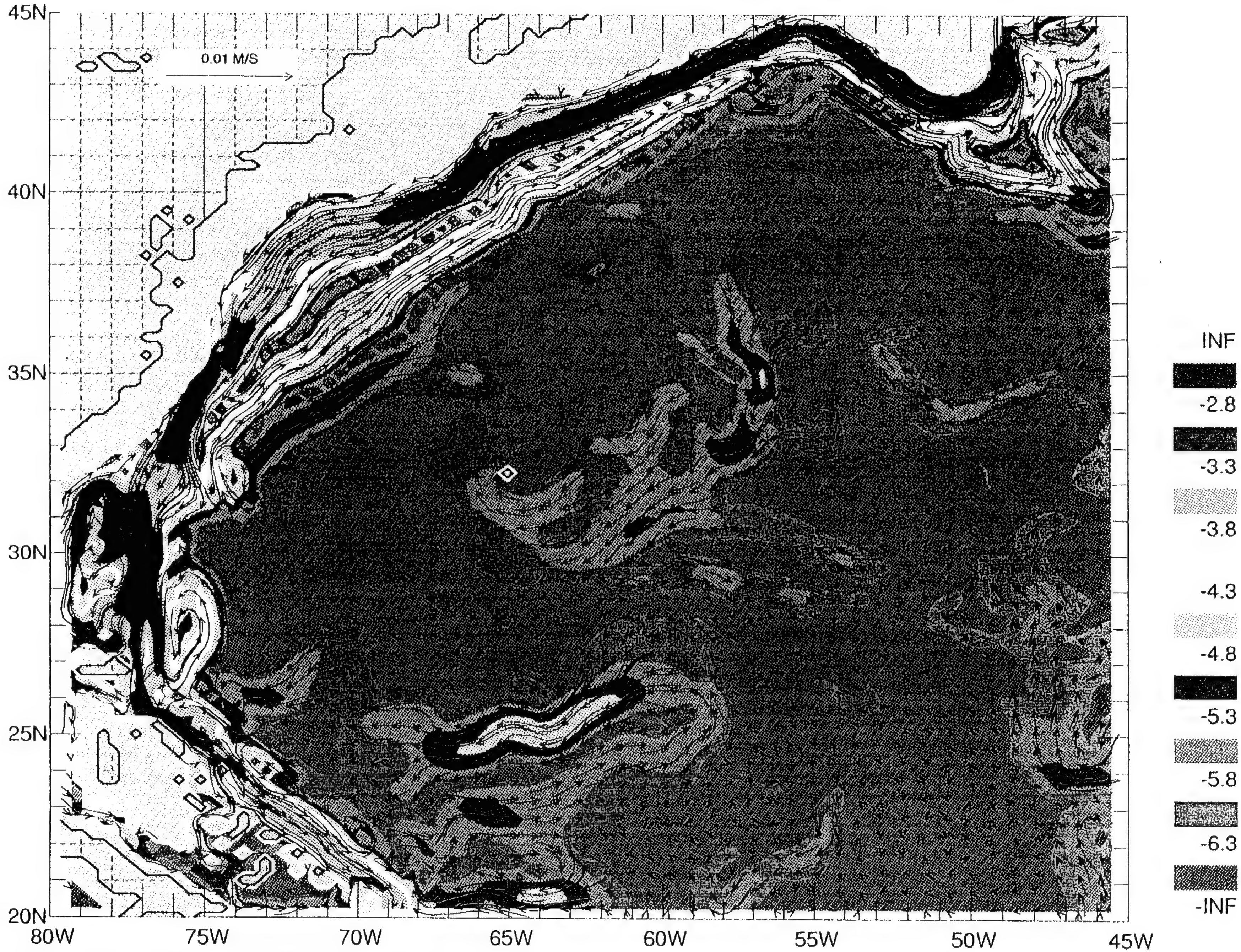


Figure 5.1.2.-3. Mean currents (arrows) in the lowest model layer and kinetic energy of the mean flow (color contours) in the western North Atlantic study area. Maximum current is 10.6 cm/s. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in the figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

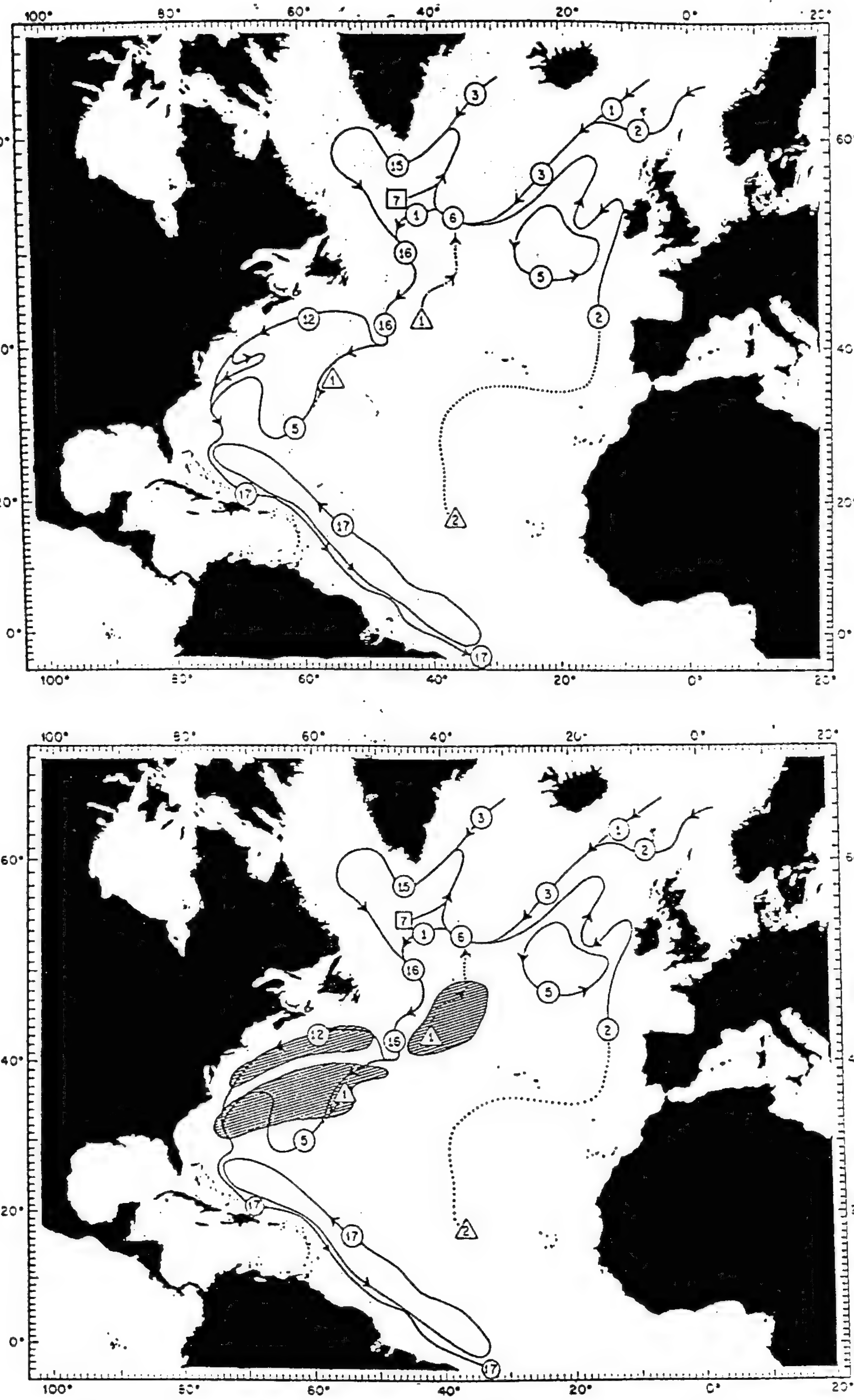


Figure 5.1.2-4. A reproduction of Figure 12 from Schmitz and McCartney (1993): "Circulation cartoon for deep water (1.8°C-4°C); (a) thermohaline forced flows only, based on McCartney (1992), and (b) with the deep mid-latitude gyres added as shaded areas. Transports are in Sverdrups, squares represent sinking and triangles represent upwelling."

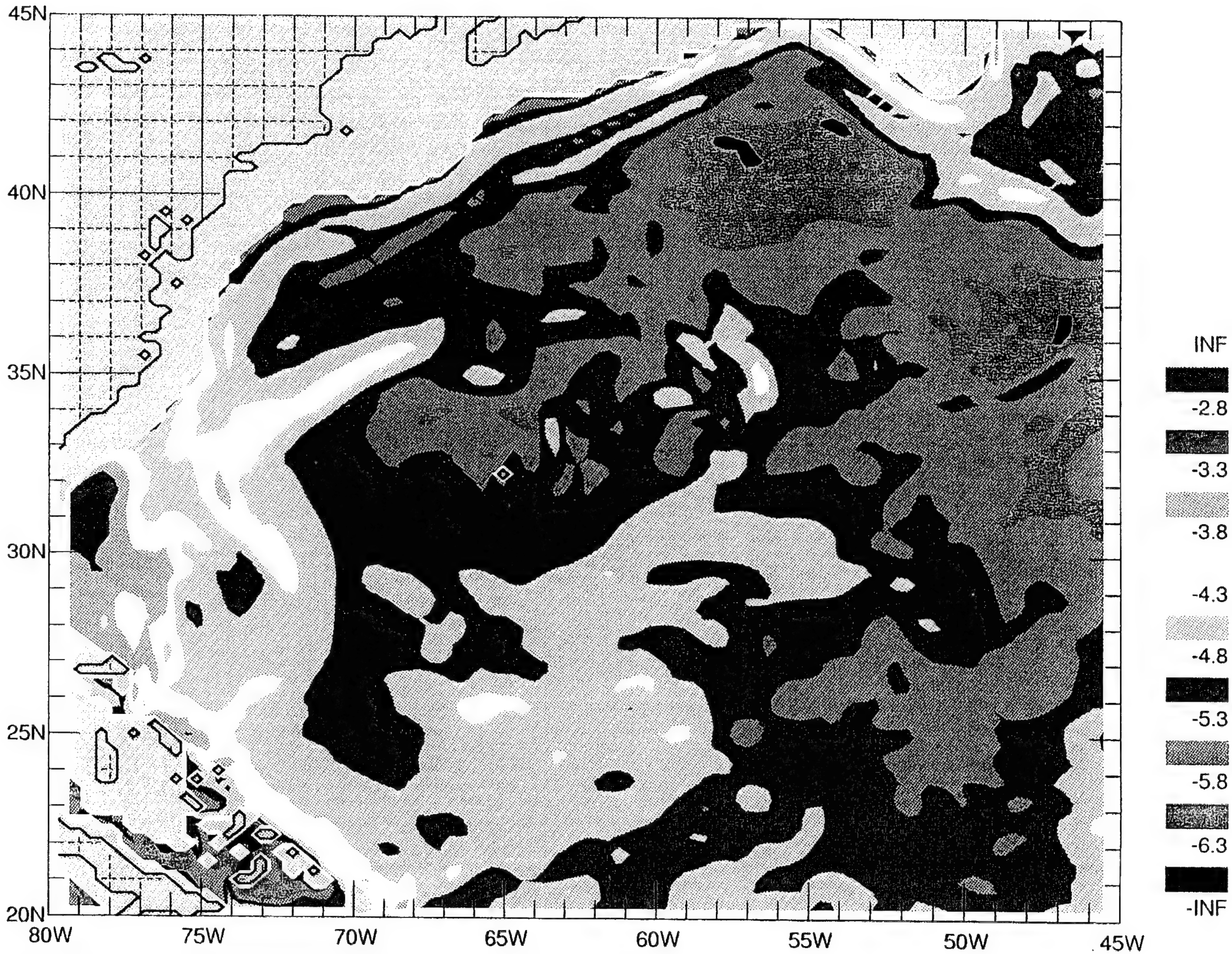


Figure 5.1.2-5. Eddy kinetic energy per unit mass in the lowest model layer in the western North Atlantic. Maximum value is approximately 18 cm^2/sec^2. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in the figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

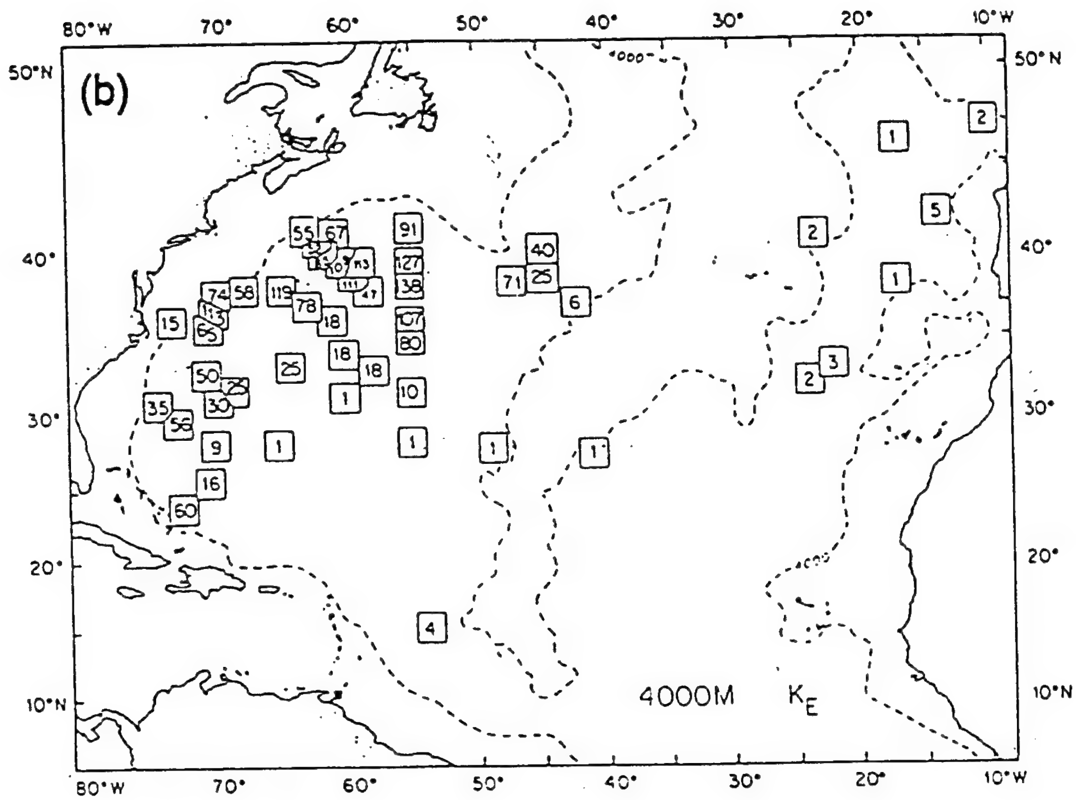


Figure 5.1.2-6. A reproduction of Figure 1b from Thompson and Schmitz (1989); "(b) Updated chart of the existing estimates of abyssal eddy kinetic energy (cm^2/sec^2) in the North Atlantic. (See also Schmitz, 1984)."

Table 5.1.2-1 Values for conversion of color variables from logarithmic to geophysical units for color bars on Figures 5.1.2-3 and 5.1.2-5.	
Logarithmic scale	Kinetic Energy $cm^2 s^{-2}$
-2.8	15.85
-3.3	5.0
-3.8	1.585
-4.3	0.5
-4.8	0.1585
-5.3	0.05
-5.8	0.01585
-6.3	0.005

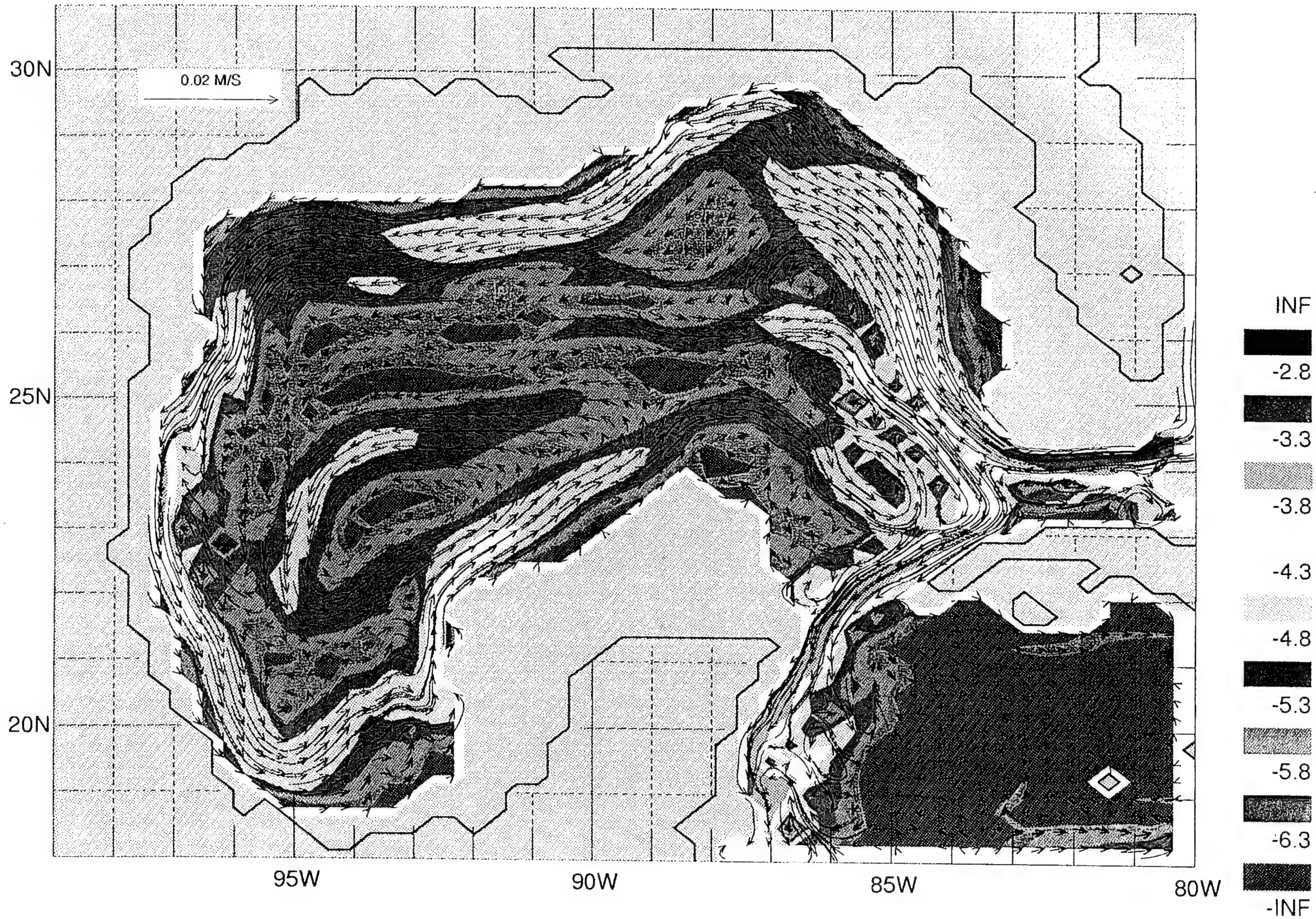


Figure 5.1.2-7. Mean current in the lowest model layer and kinetic energy of the mean flow in the Gulf of Mexico. Maximum current is 10.5 cm/s. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in the figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

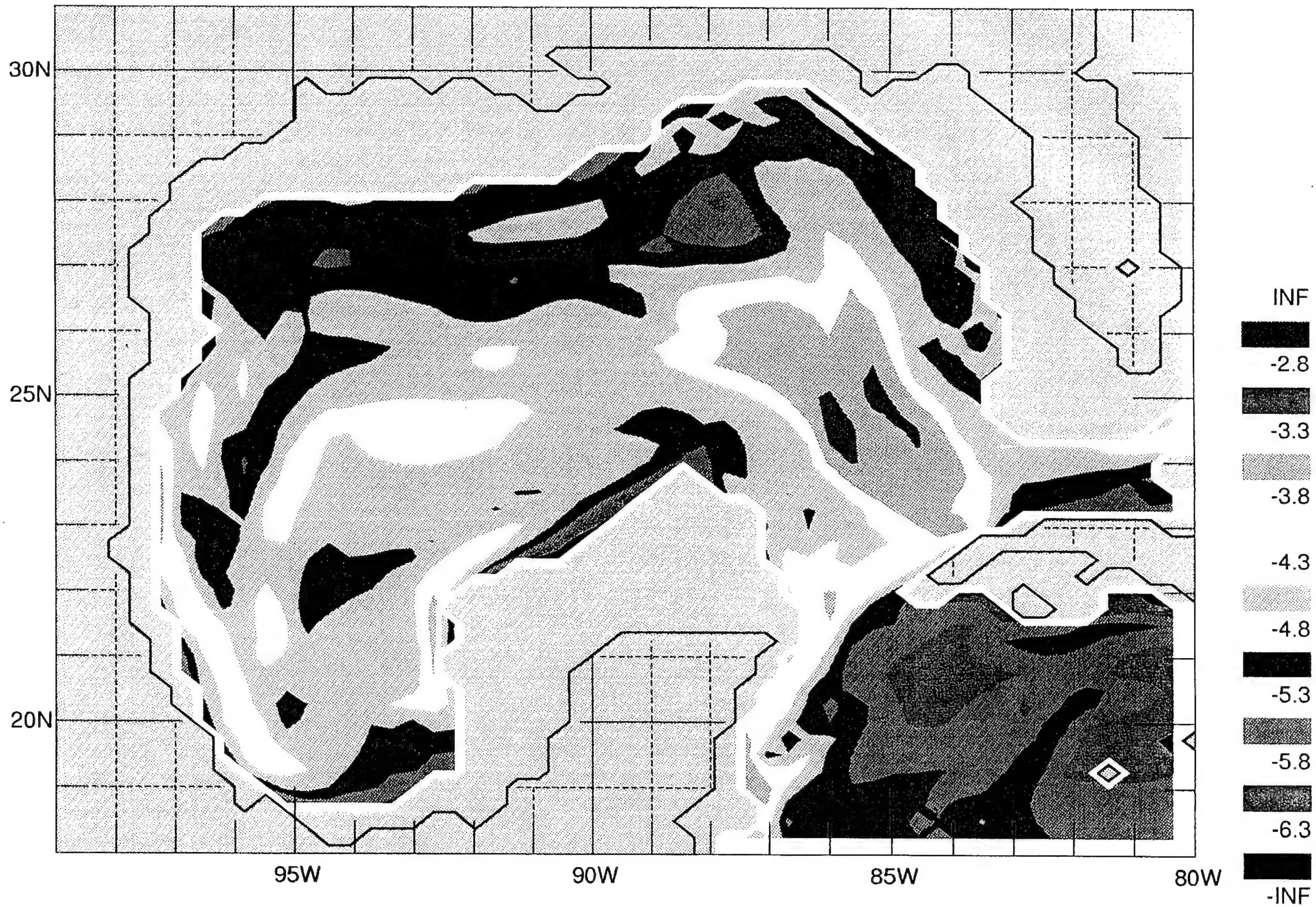


Figure 5.1.2-8. Eddy kinetic energy per unit mass in the lowest model layer in the Gulf of Mexico. Maximum value is approximately 8 cm^2/sec^2. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

current meter records (Hamilton 1990). However, the magnitude of the energy is more than a factor of ten smaller than the observed values. This is related to the problems with the Gulf Stream reported above; previous simulations of just the Gulf of Mexico have had larger eddy kinetic energy values. Regardless, both the observations and the simulations show that the mean and eddy kinetic energy levels in the Gulf of Mexico are more than 10 times greater than the levels in the North Atlantic region with strong, persistent bottom flow. There appears to be far fewer candidate sites for isolation in the Gulf of Mexico (see Section 3.3, **Site Selection Model**) with regard to physical oceanographic considerations.

The mean currents in the Pacific study area are quite small and the range of kinetic energy is less than in the Atlantic or the Gulf of Mexico (Fig. 5.1.2-9, note the change in scale for both the kinetic energy, color contours, and the mean current arrows). The purple color in the Pacific mean current plot (Fig. 5.1.2-9) is equivalent to the dark green in the Atlantic and Gulf of Mexico plots. In only a small fraction of the Pacific area, the mean currents are above this background level and then only in small, isolated eddies and whorls. In contrast, roughly half the Gulf of Mexico region and more than a quarter of the Atlantic region are greater than this energy level and both show strong persistent patterns of mean currents. Thus the dispersion of contaminants by mean advection will be small in the Pacific domain, consequently, the locations of the mean currents will not affect the site selection as strongly as they did in the other regions. This is consistent with the fact that the Atlantic study area is in the region of a western boundary current, the Gulf Stream in this case, where the coastal boundary and the Earth's rotation combine to restrict and intensify the ocean circulation. In the Gulf of Mexico, the Loop Current is about half the strength of the Gulf Stream and the eddies that are shed from the Loop Current maintain a high level of kinetic energy throughout most of the Gulf of Mexico. In the eastern Pacific, however, these processes act to diffuse the ocean circulation resulting in a broader, significantly weaker mean flow.

In the North Pacific, the model results compare quite well with data collected in several regions of the Pacific. In particular, the eddy kinetic energy in the sixth, bottom layer agrees well with observations taken in the western North Pacific (Hurlburt et al., in press, see Figure 17). In the study region there are no long time series and fewer measurements than in the Atlantic. However, the model agrees quite well with the short time series reported by Stabeno and Smith (1987). From several roughly year-long current meter moorings in the region between 38°N and 40°N and 126°W to 130°W, Stabeno and Smith show currents of less than 0.3 cm s^{-1} and eddy kinetic energy levels of approximately 1 to 10 cm^2s^{-2}. This agrees well with the model results shown in Figures 5.1.2-9 and 5.1.2-10.

The eddy kinetic energy in the Pacific domain is substantial in comparison with the Atlantic and Gulf of Mexico (again note the change of scale on the color bar). However, as we showed above, the results for the Atlantic and Gulf of Mexico are too small, possibly by a factor of as much as 100 in some cases. The energy levels in the Pacific are in good agreement with the limited observations. The high energy levels at 40°N (Fig. 5.1.2-10) are associated with the east-west Mendocino fracture zone. Strong surface jets and high seasonal variability of the surface flow are also associated with Cape Mendocino. These surface features are well documented (Strub et al. 1991) and it is expected that they would also have enhanced deep energy levels associated with them.

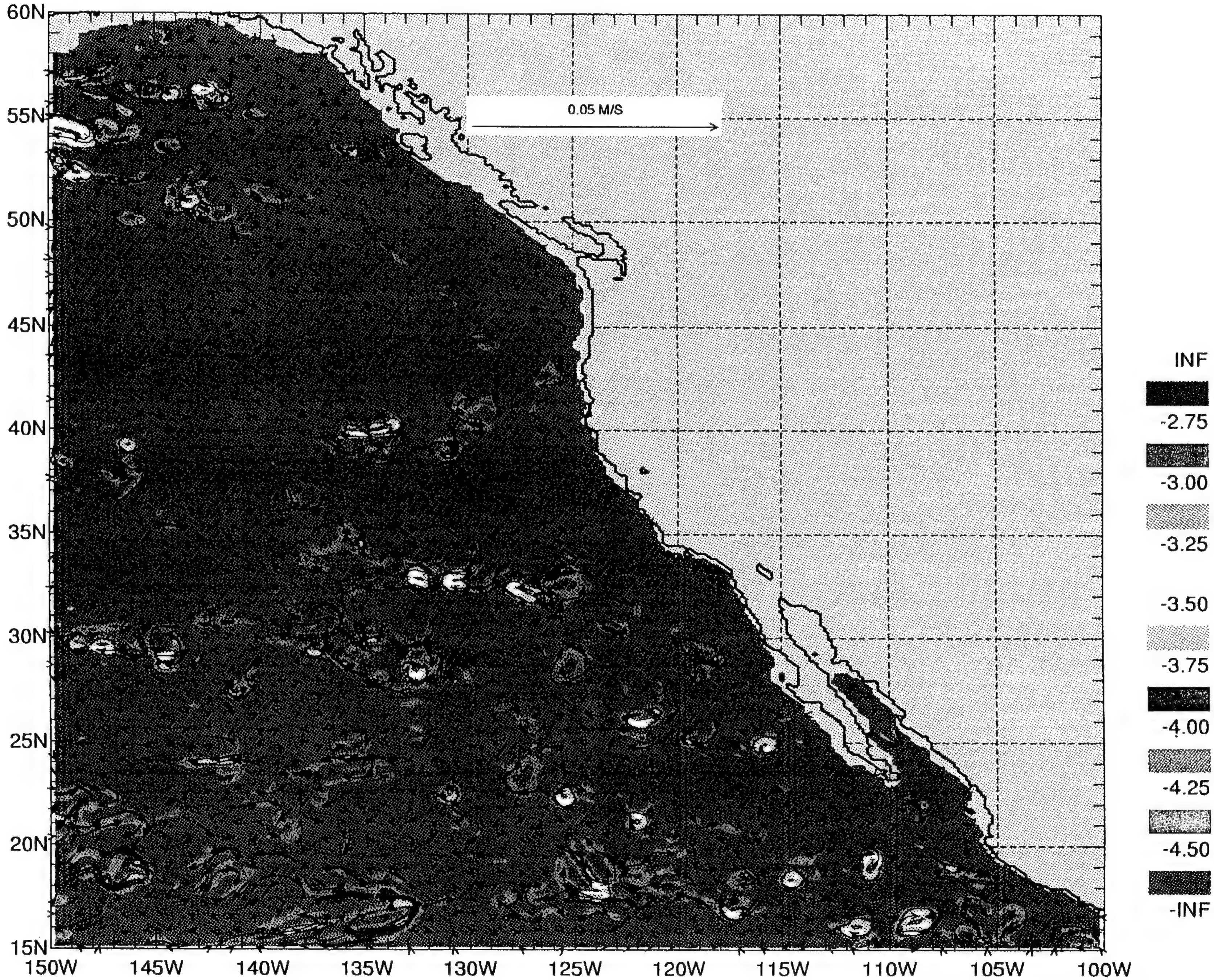


Figure 5.1.2-9. Mean current in the lowest model layer and kinetic energy of the mean flow in the eastern North Pacific. Maximum current is 10.8 cm/s. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in the figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

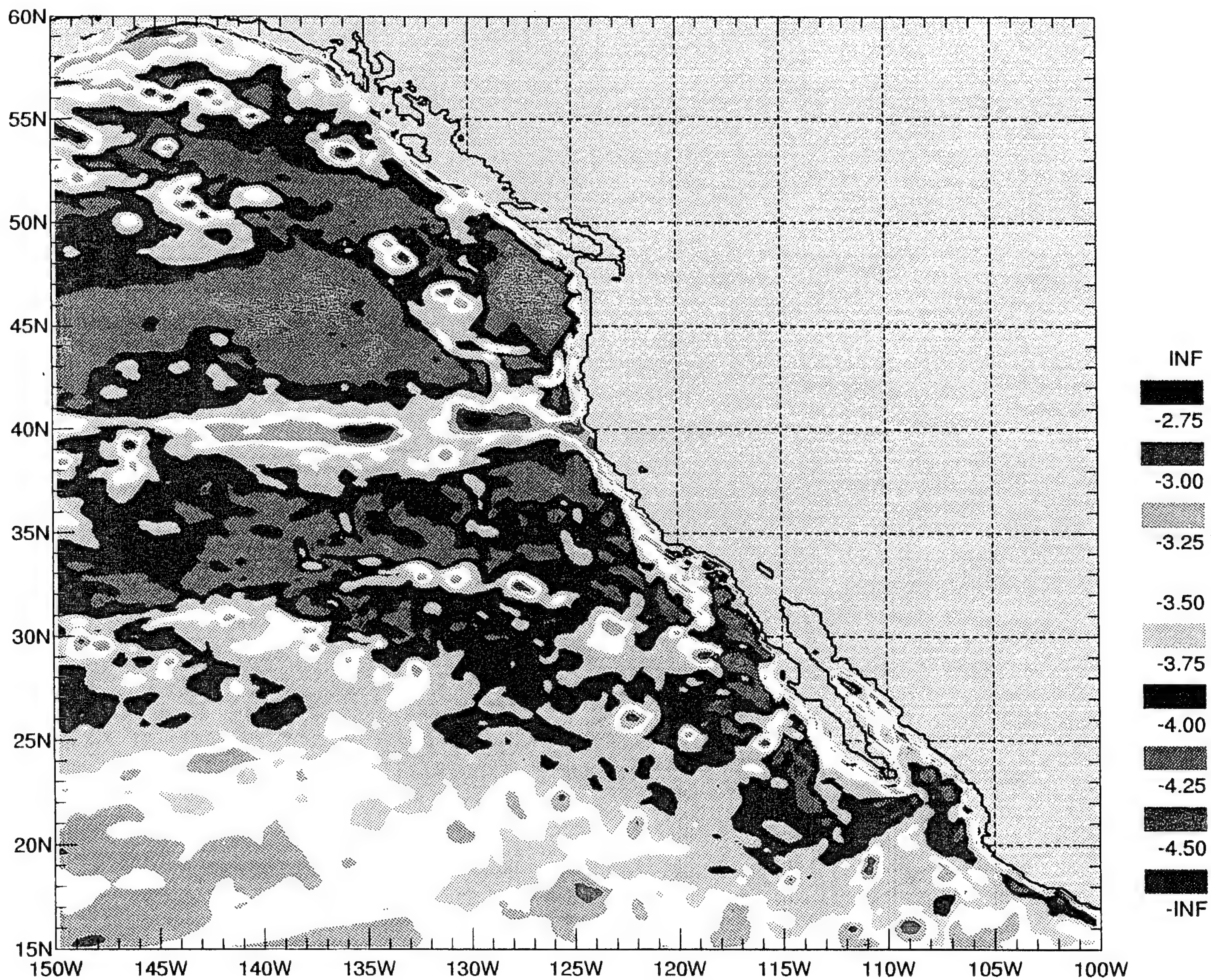


Figure 5.1.2.-10. Eddy kinetic energy per unit mass in the lowest model layer in the eastern North Pacific. Maximum value is approximately 20 cm^2/sec^2. The color bar uses a logarithmic scale to conveniently represent the large range of kinetic energy (from less than 0.005 cm^2s^{-2} to greater than 15.85 cm^2s^{-2}) shown in the figure. The conversion from logarithmic scale to physical units is given in Table 5.1.2-1.

In the Atlantic and the Gulf of Mexico where the bottom currents and kinetic energy levels are particularly significant for the potential dispersal of material from the isolation sites, we conducted a series of tracer studies at the surrogate sites selected by the working group (see Section 3.3, **Site Selection Model**). Passive tracers were released from these sites over a period of one year and their dispersion was tracked for two years from the beginning of the release (see Figs. 5.1.2-11, 5.1.2-12, and 5.1.2-13).

The distribution of the tracer concentration shows the direction and distance of the long-term advection and diffusion of water parcels from the surrogate isolation sites. These tracer release experiments do not account for the aggregation and sinking of the particulate material (see the plume model discussed below), and they do not account for biological or chemical processes. Thus, the tracer concentration distribution shows the maximum area that could be affected by the physical dispersion of contaminants from the isolation sites. Even though we ignored many factors that would further reduce the level of contaminants in the water, the level of tracer in the water is less than 10% of the original concentration for distances more than 5° (approximately 500 km) from the dump sites (see discussion below).

The tracers from both Atlantic-1 (Fig. 5.1.2-11) and Atlantic-2 (Fig. 5.1.2-12) disperse in a general southwestern direction. This is consistent with the direction of the mean flow at the sites (Fig. 5.1.2-3). The advection at Atlantic-1 is greater than at Atlantic-2 because the mean current is stronger, particularly just southwest of the site. The north-south diffusion at Atlantic-2 is somewhat greater than at Atlantic-1 due to the greater eddy kinetic energy just north and south of Atlantic-2.

In the Gulf of Mexico, the tracer dispersion is governed more by turbulent diffusion than by mean advection; however, there is some indication of eastward advection north of the isolation site and southeastward advection south of the site. The areal extent, about 5°, of the dispersion of the tracer, is similar to that in the North Atlantic, although there are substantially greater areas of low mean current and eddy kinetic energy in the Atlantic. This demonstrates the importance of careful, quantitative site selection. In the Atlantic, the surrogate sites were in or near high-energy areas. This can be avoided in the final site selection; however, dispersion by physical processes is not the only site selection criterion.

The tracer release experiments showed that the dispersion of tracers from the surrogate sites was relatively small even after three years, but nowhere in the ocean is the water stagnant. Eventually the water parcels that pass over the dump sites will appear at the surface of the ocean either intact or mixed with other water masses. However, if we choose the sites carefully, it may take 400 years to as much as 1000 years before the water reaches the ocean surface (see Section 5.1.1.3(1), **Northwest Atlantic Abyssal Flow Characteristics**).

(2) Plume Model

Our reason for conducting the experiment with the WES STFATE model was to obtain more realistic estimates for the residence time of particulates in the water column. Values

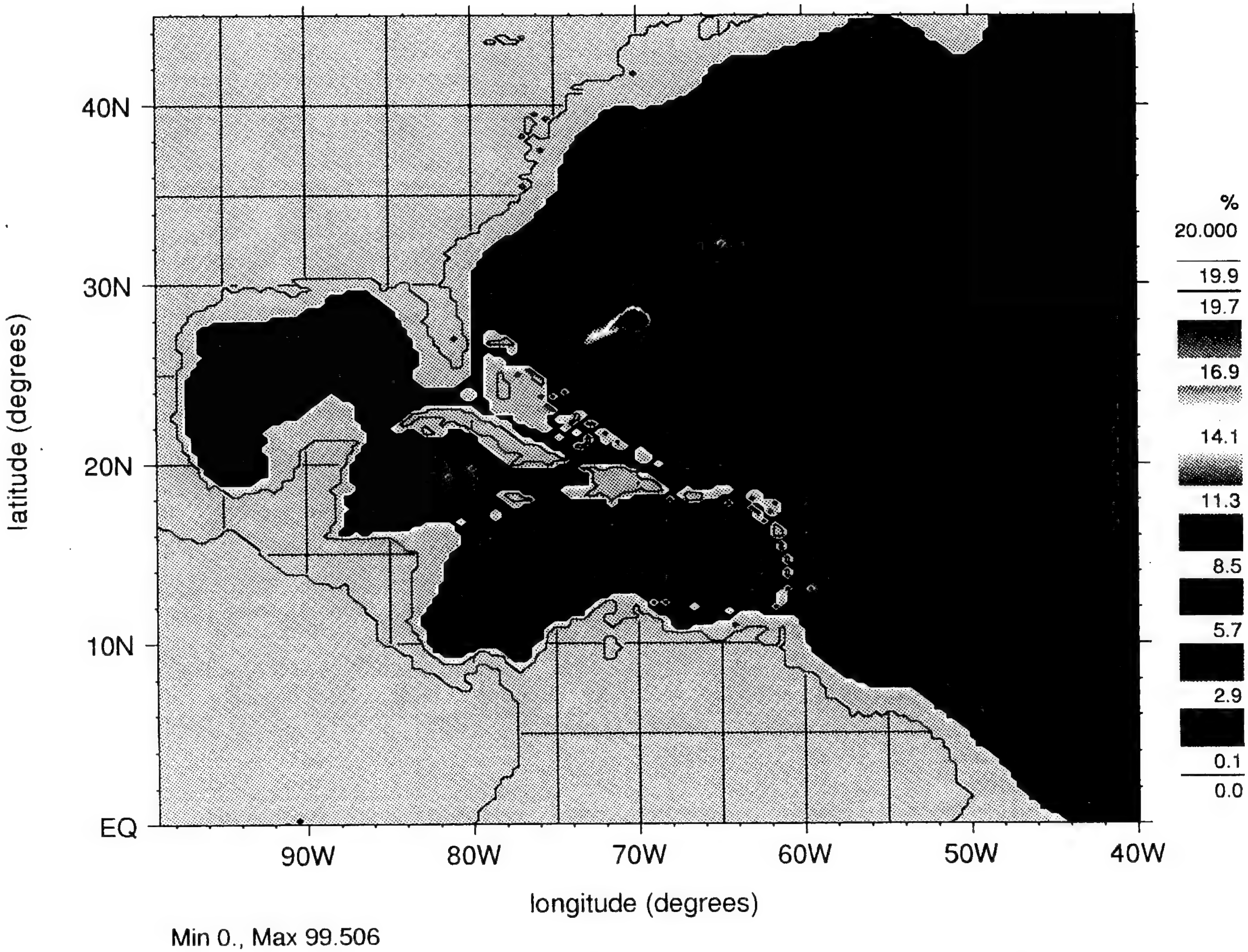


Figure 5.1.2-11. Concentration of tracer released from site 1 in the western North Atlantic two years after release was initialized.

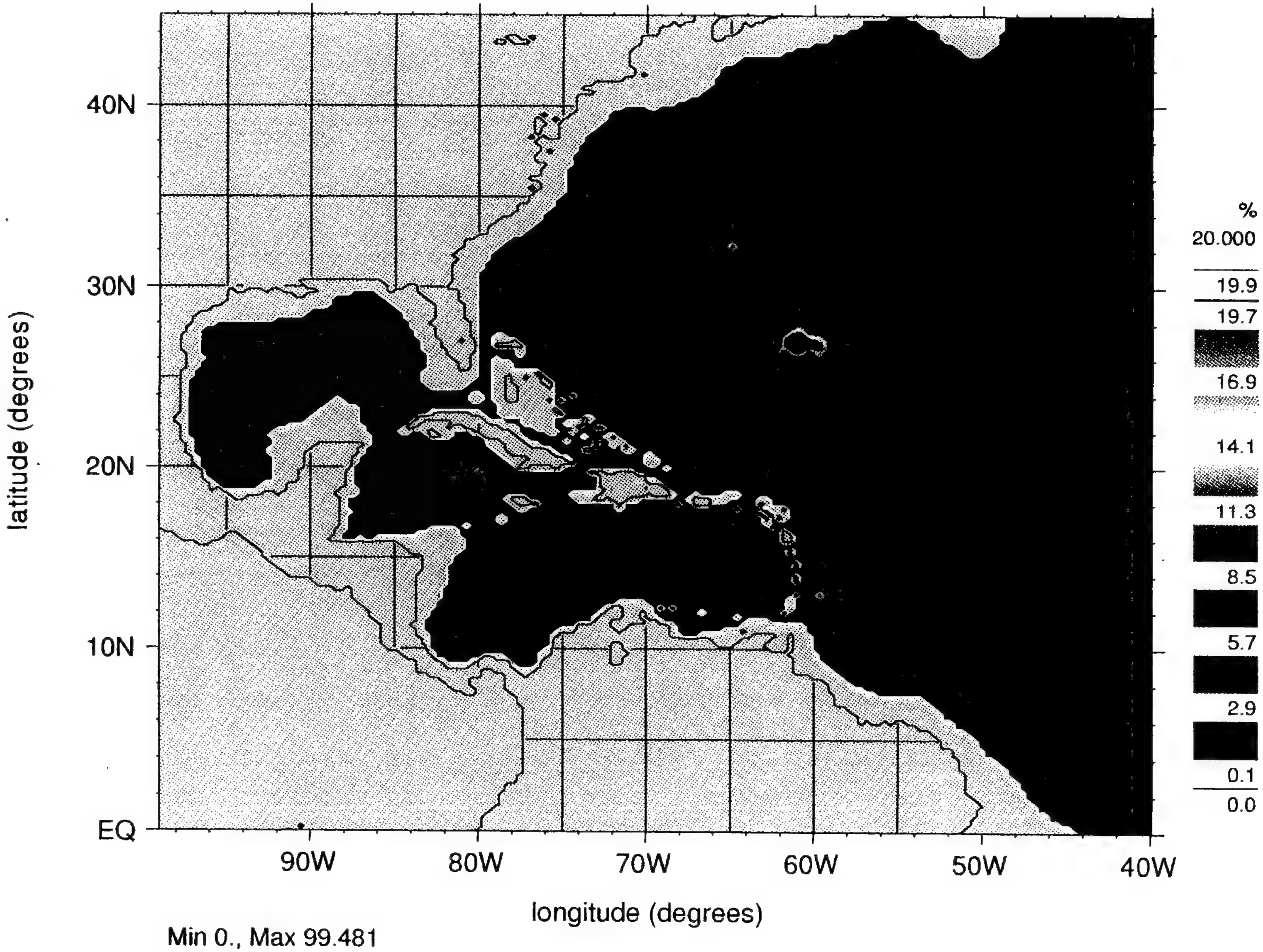


Figure 5.1.2-12. Concentration of tracer released from site 2 in the western North Atlantic two years after release was initialized.

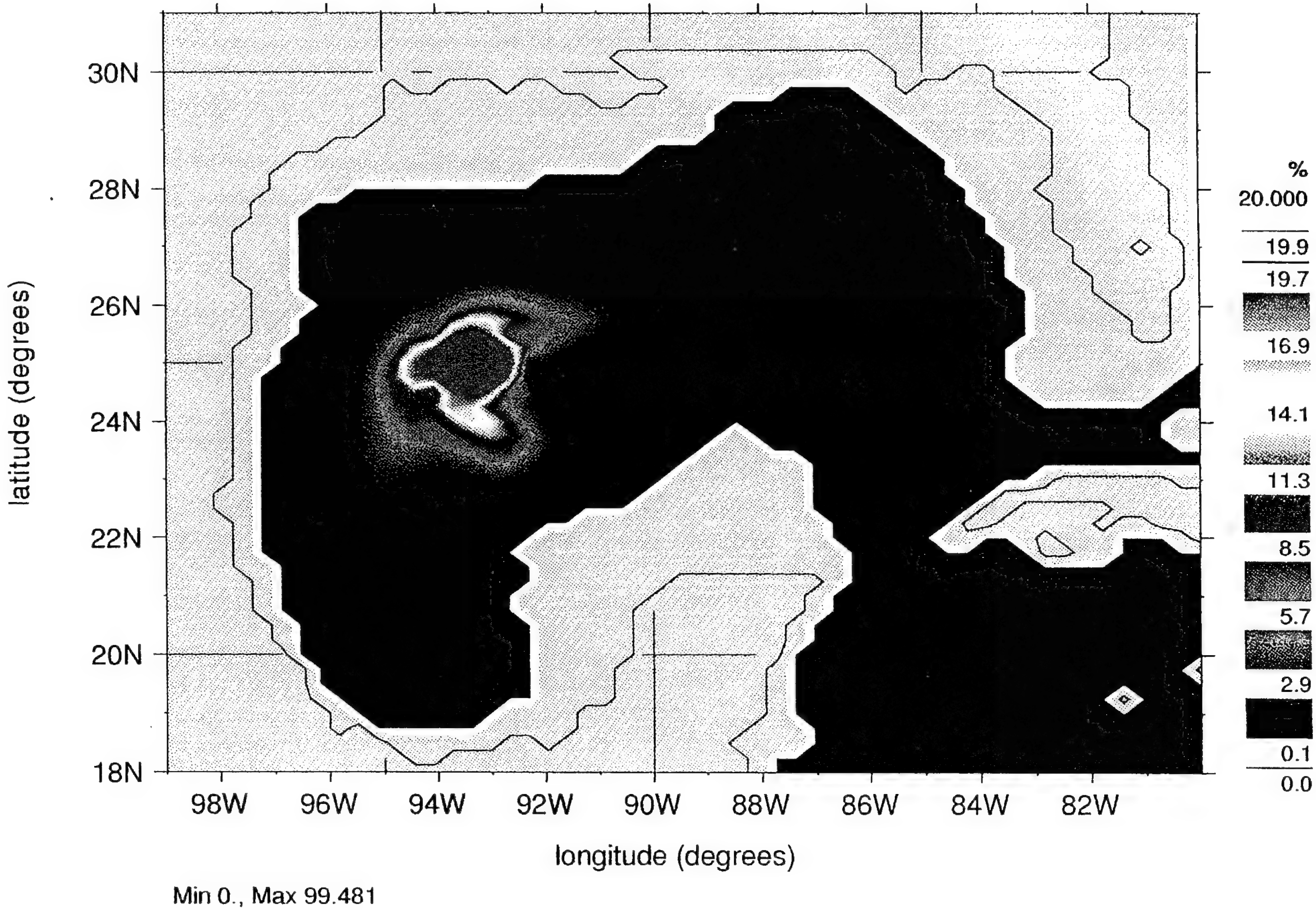


Figure 5.1.2.-13. Concentration of tracer released from the Gulf of Mexico surrogate site two years after release was initialized.

based solely on Stoke's settling velocity may overestimate the residence time because processes such as aggregation are neglected. In the STFATE model the dispersion of the material is parameterized utilizing several convecting clouds which may have varying properties. The model allows for fine and dissolved material to be stripped away from the convecting clouds. The stripped material is then handled with a series of Gaussian clouds that expand due to turbulent diffusion and sink. If the material is cohesive, the settling velocity becomes a function of concentration.

The preliminary plume experiment consisted of a split hull barge dump simulation using the STFATE model. The dump was in two parts from a stationary barge. The waste stream consisted of the three particulate concentrations detailed in Table 5.1.2-2. The waste also contained pore water with a density of 1.023 Mg/m^3, the default estimate of the density of the water in dredged material from the STFATE model, and an initial concentration of lead of 0.174 mg/l. The volume of layer 1 is 1500 m^3 with 75% of the volume being water and 800 m^3 for layer 2 with 65% of the volume being water. The ambient density was 1.0287 Mg/m^3, which is consistent with the conditions at 3000 m in the North Atlantic (Speer and Rona 1993). The simulation included two dumps and two hours of settling and mixing in a 90-m-deep water column (the maximum allowable depth in the STFATE model). A typical simulation for this model is 1 hr in 12 m of water, so we are pressing the limits of the parameterizations.

After 300 seconds the convective descent and dynamic collapse phases terminated when the rate of spreading became less than the rate of spreading due to turbulent diffusion. At this point all the clumps had hit the bottom; 6% of the sand and 96% of the clays were still in suspension. After 3000 seconds all the sands had fallen to the bottom. At the end of the 2-hr simulation 33% of the clays were still in suspension and all the dissolved lead was still in the water. Because of the cohesive nature of the clays the sinking velocity calculated during the experiment was 0.12 cm/s for the clays in layer 1 and 0.16 cm/s for the clays in layer 2. This is 2 to 2-1/2 times greater than the Stoke's settling velocity for clays (see Table 5.1.1-2).

This experiment shows that the settling velocities can vary significantly from Stoke's values and that was the main purpose for the experiment. However, most of the questions relating to the dynamics of plumes of waste from ruptured bags remain unanswered. These plumes would not hit the bottom; they will rise to a depth just above their neutrally buoyant depth, approximately 200 m off the bottom, and slowly sink to the neutral buoyancy depth. The particles suspended in the water will slowly sink out and the water, with any dissolved material, will spread and advect vertically and horizontally. The extent of the spreading will depend on the ambient mesoscale and large-scale flow fields and vertical density gradient. The plumes will probably entrain less ambient water than this experiment suggests since the background level of turbulence will be much lower than the level assumed by the model.

Table 5.1.2-2 Characteristics of materials discharged from barge in STFATE tests				
Material	Specific Gravity, Bulk Specific Gravity	Volumetric Concentration Layer 1	Layer 2	Settling Velocity (cm/s)
clumps	1.6	0.1	0.0	90.0
sand	2.7	0.2	0.15	3.0
clay*	2.65	0.05	0.1	0.06
* the clay is designated as a cohesive particulate				

5.1.2.3 Conclusions

We have analyzed dispersion by the physical processes of advection and diffusion as one site selection criterion and have examined its causes and variability in the North Atlantic, Gulf of Mexico, and North Pacific study areas. The dispersion by the large-scale flow is a significant site selection criterion in the North Atlantic and the Gulf of Mexico study regions, but is only important in limited areas in the Pacific.

We have looked at the effects of the large-scale ambient flow field on the dispersion of waste from the surrogate isolation sites in the North Atlantic and Gulf of Mexico using tracers. The more important process in the Atlantic appeared to be advection, whereas diffusion appeared to be more important in the Gulf of Mexico. We have found that the simulated currents and eddy variability were useful tools although some deficiencies existed in the magnitude of the eddy kinetic energy in the North Atlantic and Gulf of Mexico regions. Despite some underestimation of the magnitude of the eddy kinetic energy, the location of maximum energy agreed well with observations. Thus it can be used as a tool for site selection and analysis.

We examined a model of surface dumping of dredged material and concluded that it is not adequate for modeling the waste plumes that could occur during, or as a result of, deep-ocean disposal of waste materials. However, the model results did point out the importance of properly handling aggregation of suspended particulates. We will include particles in a nonhydrostatic plume model for future studies.

We conclude that the submesoscale to mesoscale regimes (less than 1 km to 100 km) will probably be the most affected by any dispersion of the waste material. With information on the ambient larger scale flows in hand, we can now model realistically the mesoscale regime.

5.2 Geology and Geophysics

5.2.1 Bathymetry and its Derivatives *by Peter R. Vogt and Woo-Yeol Jung*

5.2.1.1 Introduction

Bathymetry is the process of measuring water depth and producing topographic displays (maps, profiles). Analysis of the submarine land forms, in terms of the processes that created the land forms and those which are modifying them today, falls into the discipline of geomorphology.

Bathymetry impacts on the abyssal seafloor waste isolation option in the following distinct ways:

(1) **Congressional Tasking**: By definition, only "abyssal" areas are considered for this project, where abyssal here is defined as "deeper than 3000 m." Thus, bathymetric charts/databases are needed to define all areas below the 3000-m isobath. (For exact tasking, see Section 1.1.2, **Background**.)

(2) **Engineering Requirements**: Water depth at potential waste isolation sites needs to be known for engineering and economic modeling. For example, the deeper the site, the longer it takes a container or vehicle to reach the seafloor and/or to make a round trip.

(3) **Sediment Slope Instability**: Local topographic highs and steep topographic slopes need to be known so that waste isolation sites are not inadvertently selected on or too close to these areas. Sites close to a steep-sided high could be buried by a local turbidity flow or debris flow, whereas material close to a low might slide or be carried into that low. Material placed on a slope will tend to move in the downhill direction unless bottom currents are involved (see below).

(4) **Scour Enhancement**: Seafloor relief (particularly major topographic highs) will influence bottom-water circulation and therefore possibly sediment/pollutant resuspension and redistribution. Bottom currents generally accelerate as they circumvent seamounts, and as a result scour seafloor sediments, producing moats. Waste material placed in a moat area will tend to be resuspended if it is loose, or if in a container, will move downward and tilt if the sediment surrounding the container is eroded.

(5) **Prediction of Pertinent Processes and Properties**: Over most of the ocean floors, bathymetry is the only type of geological data available. Fortunately much can be inferred about both seafloor processes and seafloor geology (i.e., physical properties) from a good bathymetric map. Because the seafloor substrate has a strong influence on the benthic biology, bathymetry is also a good guide to faunal associations. Abyssal plains and abyssal hills physiographic provinces are both attractive for abyssal waste isolation. Large, nearly horizontal abyssal plains (with slopes by definition less than 1:1000) are almost certainly formed by continent-derived *turbidites*, horizontally stratified (sheetlike) deposits from suspension flows, many of which carried terrigenous sediment and organic matter from as high as the continental shelf edge, and then deposited these in the abyss. Turbiditic sediments become progressively finer and the individual deposits thinner with increasing depth, i.e., distance downslope on the abyssal plain. Thus, from the bathymetry alone (see Figs. 5.2.1-1 through -3) we can conclude that both of the Atlantic sites and the Gulf of Mexico surrogate waste isolation site are underlain by turbidites and thus have been crossed by numerous turbidity (suspension) flows. While such flows are known to have been more common during glacial sea-level lowstands (most recently 25,000 to 18,000 years ago) than they are today, turbidity flows have also occurred in historical times (e.g., the flow which spread out across the Sohm Abyssal Plain after the 1929 Grand Banks earthquake, breaking telephone cables in the process). There is no reason to believe that suspension flows would not in the future cross the Gulf of Mexico and Atlantic sites — it is only a question of probability. If a long-term average recurrence rate can be determined from cores at potential waste isolation sites, such a rate can probably be assumed to give an upper bound to the probability of such flows crossing a waste isolation site in the coming decades or centuries. In addition, the bathymetry shows that the Atlantic-2 Site is located in a fracture zone valley at the outermost, deepest end (6010 m) of the abyssal plain system which extends from the southwestern Sohm Abyssal Plain through the Hatteras to the Nares Abyssal Plain. The bathymetry alone predicts that turbidites are thicker, sediment particle size coarser, and the causative suspension flows faster and more frequent at Atlantic-1 (5438 m, Hatteras A.P.) compared to Atlantic-2, which apparently has only been reached by

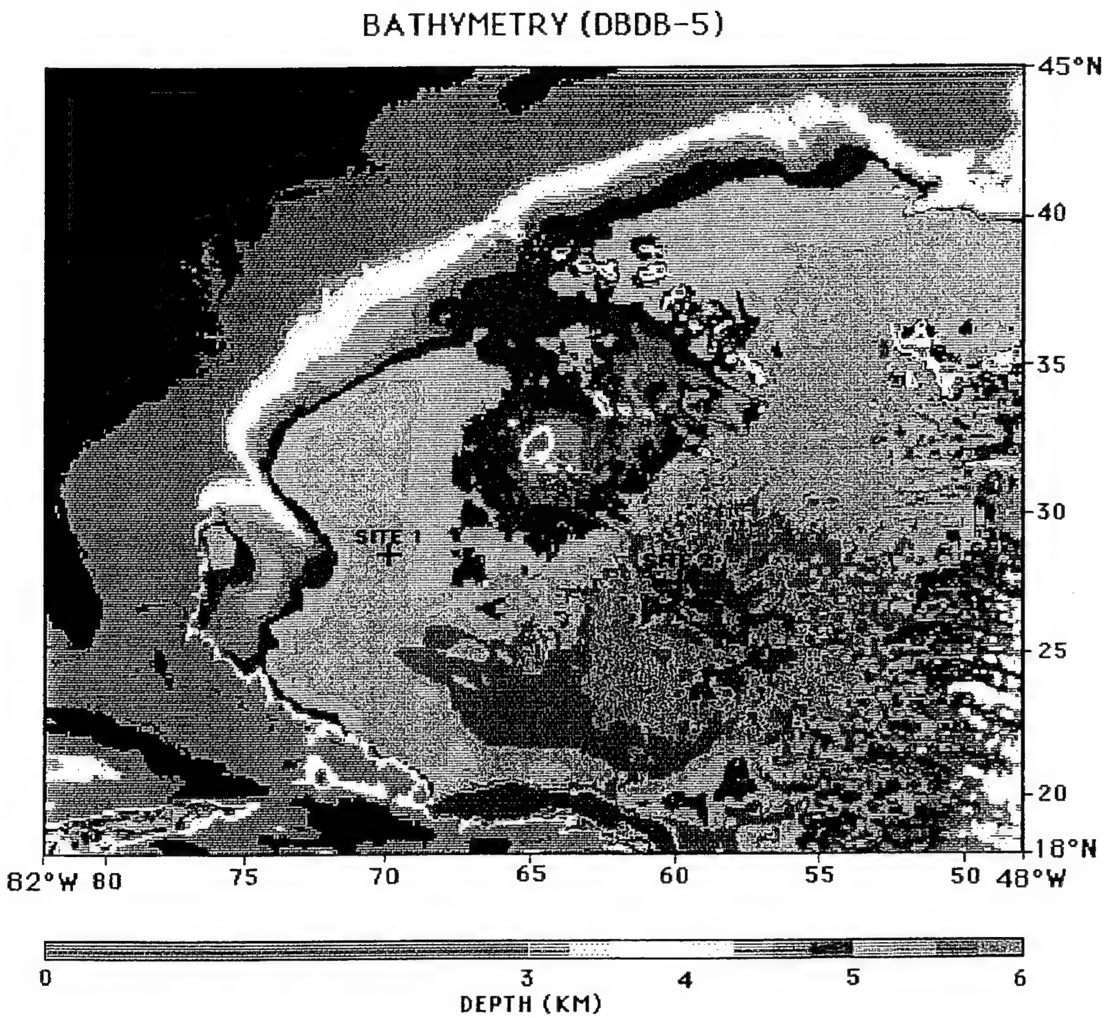


Figure 5.2.1-1. Bathymetry of western north Atlantic, derived from 5′ latitude × 5′ longitude DBDB-5 gridded data set. Land is black, water depths less than 3000 m are gray, and deeper waters are depicted with color changes every 250 m deep. Two surrogate relocation sites are indicated by crosses. Mercator projection.

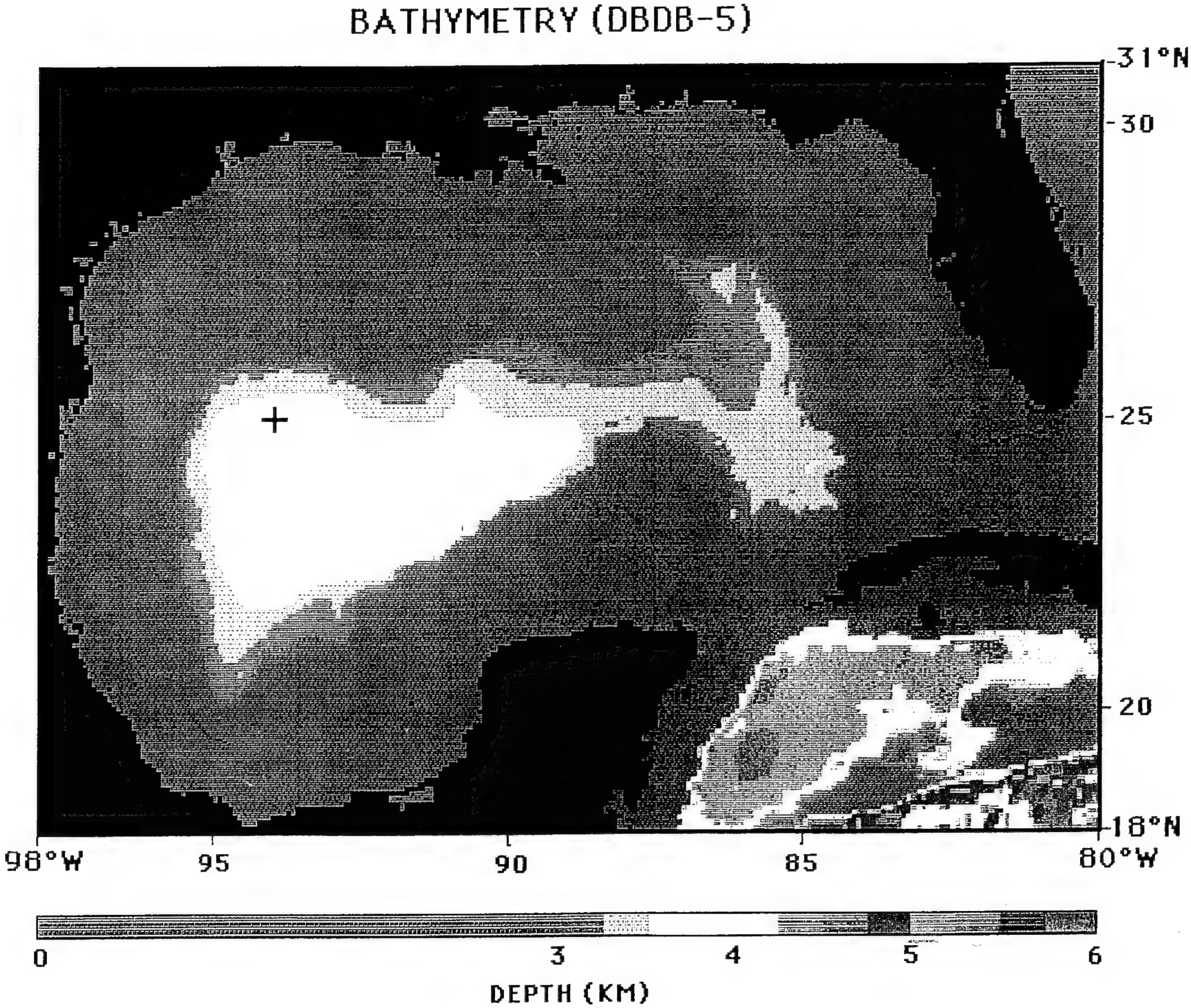


Figure 5.2.1-2. DBDB-5-based bathymetry for Gulf of Mexico, with cross indicating surrogate relocation site. Land is black, water depths less than 3000 m are gray, and deeper waters are depicted with color changes every 250 m deep. One surrogate relocation site is indicated by cross. Mercator projection.

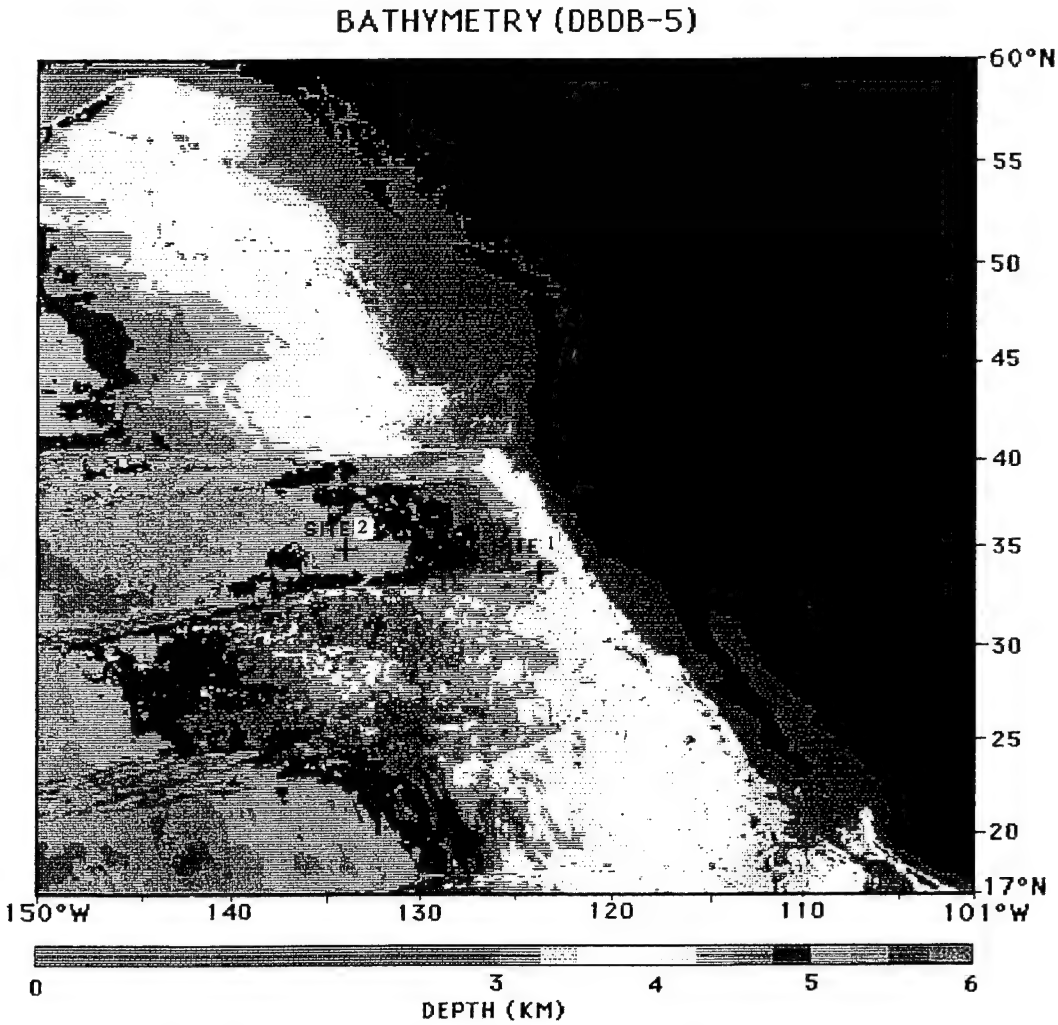


Figure 5.2.1-3. DBDB-5-based bathymetry for eastern Pacific, with crosses indicating surrogate relocation sites. Land is black, water depths less than 3000 m are gray, and deeper waters are depicted with color changes every 250 m deep. Two surrogate relocation sites are indicated by crosses. Mercator projection.

a handful of such flows in 1–2 million years. Furthermore, if the clay/silt ratio helps determine benthic faunal assemblage, then the two sites can be expected to exhibit biologic differences in addition to what can also be predicted from the bathymetry, viz., there will be less living benthic biomass per unit area at Atlantic-2 compared to Atlantic-1 (see Section 2.4.3).

The two Pacific surrogate sites are also located in relatively flat, horizontal areas. However, as these are located beyond the reach of land-derived suspension flows, the turbidites under the Pacific sites could only have come from nearby seamounts or abyssal ridges. The bathymetry in this case predicts infrequent, small-volume flows composed mainly of hemipelagic sediments (including nannoplankton and foraminiferal tests) and/or red clays.

Although abyssal plain sites are preferred for waste isolation purposes, the geology/biota of nearby steep-sloped or abyssal ridges have to be considered in case the target area is accidentally missed. In addition, pollutants (sensu lato) or nutrients released from waste isolation sites are likely to be wafted across such local highs. Local slopes of 10°–20° or more are likely to be underlain by older, semiconsolidated sediment, altered igneous rock such as basalt, or "manganese" pavement. These substrate types are present because of very low sedimentation rates and intermittent slumping/sliding of sediment previously accumulated. Biota present on such slopes will include those evolved to attach to hard substrates. In addition, demersal fish (like the wreckfish, found at 500–1000 m depths) may use any holes or cracks for cover or may "graze" on sessile biota anchored to the outcrops. Finally, it is not known whether or not any species with several life forms, during different stages, inhabit both the hard substrates of steeply sloping abyssal hills/seamounts and the soft sediments of surrounding abyssal plains. If they do, waste emplacement activity on abyssal plains will influence biota on nearby topographic highs. In addition, demersal fish may be attracted from their regular habitat near abyssal hills to feed or even spawn on waste isolation sites on the abyssal plains if prey organisms are plentiful there. While accurate bathymetry does not provide evidence for any of the above, it does provide a geographic basis for experiment design.

(6) **Waste Mound Impact on Currents**: Whether placed in rigid or flexible containers, or uncontained, waste material deposited in great volume in one restricted area will alter the bathymetry, and thereby the bottom currents. While such "artificial" bathymetric relief will be relatively slight (perhaps up to 10s of meters) compared to most abyssal hills, it will be substantial compared to the very level abyssal plains. Any waste-generated mound will need to be mapped bathymetrically as it grows in height and horizontal dimensions. Although surface-ship bathymetric/sidescan monitoring of these piles is possible and relatively cheap, deep-tow bathymetric mapping would be needed at intervals (see Section 4.0, **Site Survey and Monitoring Plan**).

5.2.1.2 Bathymetry – General Principles

Bathymetry is the process of measuring seafloor water depth and producing therefrom realizations of underwater topography in the form of profiles or maps on which the data may be displayed as depth contours (isobaths), perspective and shaded relief representations,

or color-filled pixel maps (Vogt and Tucholke 1986). Since echosounding was invented in the 1920s, water depths have been calculated from the round-trip travel time of acoustic pulses reflected or scattered from the seafloor. Knowledge of the sound speed structure below the measurement platform is essential for accurate bathymetry. Computer storage of bathymetric data generally comprises either semiraw data (a string of edited soundings, each with a latitude and longitude), digitized contours, or uniformly gridded datasets derived from the soundings or from the contours.

Sounding density, depth accuracy, distribution, and navigation accuracy vary widely over the ocean basins. The best available large-area bathymetric surveys have been conducted with Global Positioning System (GPS) navigation and using hull-mounted multibeam systems which yield swaths of accurate data up to several times the water depth in width. When the survey tracks are parallel and the swaths overlap, the seafloor is 100% mapped down to some spatial resolution which, at abyssal depths, is generally a few meters vertically and a few hundred meters horizontally. Greater resolution can only be obtained with systems deployed closer to the bottom (and necessarily at lower speeds). Only a small fraction of 1% of the abyssal seafloor has been mapped with such deep-tow systems.

Most abyssal seafloor regions have not been systematically mapped with overlapping multibeam swaths. In some areas there are systematic parallel-line surveys with data gaps between the tracks covering 25% or even 75% of the total area. Many ocean regions lack multibeam data altogether. In such regions the bathymetric data set available generally consists of irregularly spaced, irregularly oriented, single-beam sounding lines with variable navigation accuracies (from a few hundred meters to 10 km or more). Geologically realistic computer contouring/gridding of such datasets has proven difficult or impossible. As a result, it has proven necessary to use geologically-trained seafloor cartographers to "interpret" the sounding sheets with hand-drawn isobaths which then in turn are digitized and computer-gridded. DBDB5 (Digital Bathymetric Database gridded at 5′ latitude × 5′ longitude cell dimension) is the only global bathymetric gridded database available today, and although locally incorporating some multibeam data, was produced in this manner (the ETOPO-5 dataset is a combination of DBDB5 and the land topography).

DBDB5, used in this and other chapters, is useful for regional assessments. However, users should keep in mind that: (a) the original contours which were digitized to produce DBDB5 contain all the errors present in the "raw data soundings" as well as additional "interpretational" errors, great or small, inherent in connecting isobaths from one sounding line to the next and (b) the process of computer gridding on a 5′ × 5′ cell size acts as a low-pass filter, removing or strongly attenuating bathymetric features ca. 10 km or less in horizontal dimension. A long, narrow, knife-like fracture zone ridge or a narrow, meandering abyssal channel may be very important for waste isolation site performance by blocking or localizing bottom water or sediment movement, respectively, but may well be completely missing from displays of DBDB5 data (such as Figs. 5.2.1-1 through -3).

Local seafloor topographic slope and relief are important parameters for the choice or elimination of potential waste isolation sites. Although these parameters are readily computed from DBDB5 (Figs. 5.2.1-4 through -6), the following limitations should be kept in mind: the slopes computed from DBDB5 (generally from a few tenths of a degree to a few

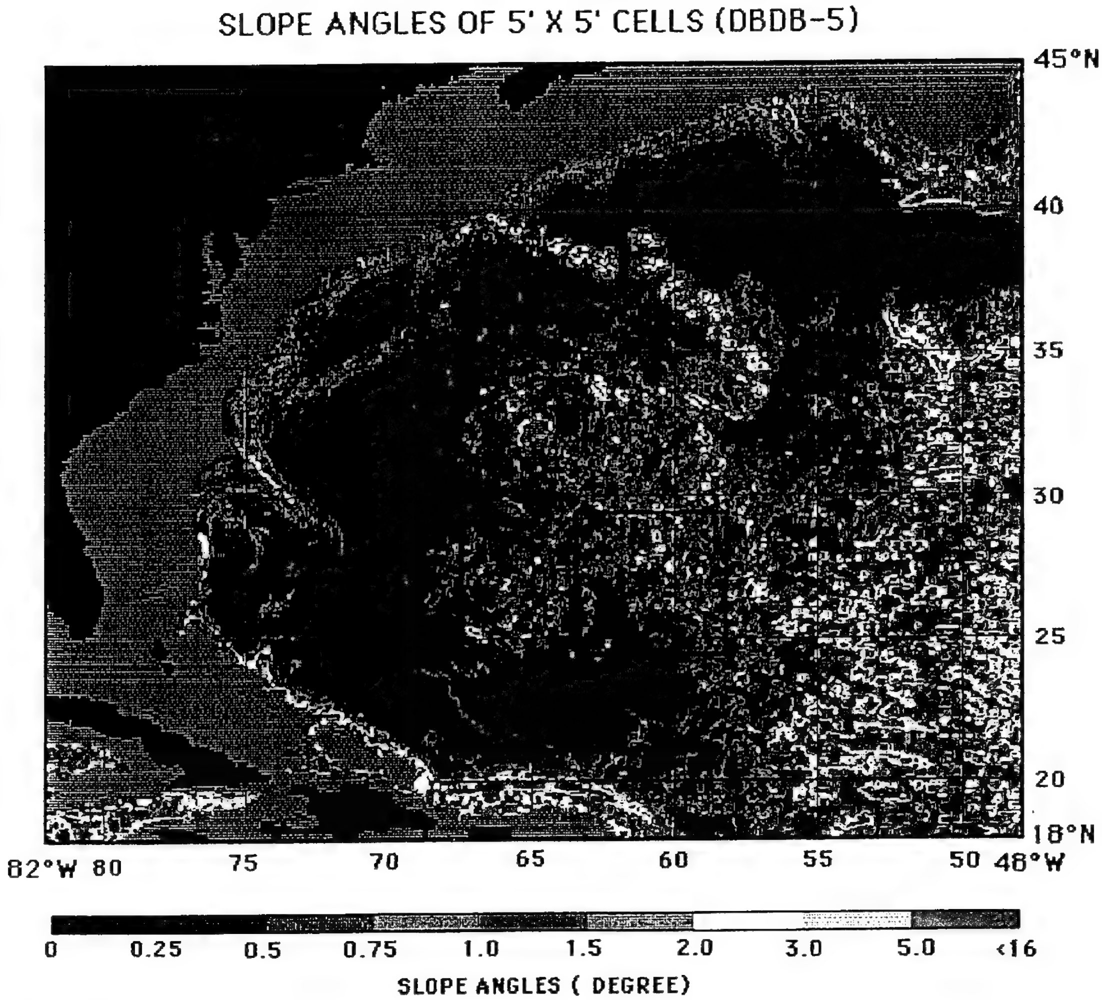


Figure 5.2.1-4. Seafloor slope angles, computed from DBDB-5 gridded bathymetry in western north Atlantic (Fig. 5.2.1-1). 5° × 5° areas (boxes) surround the surrogate sites. Areas shallower than 3000 m (gray) were omitted from calculation.

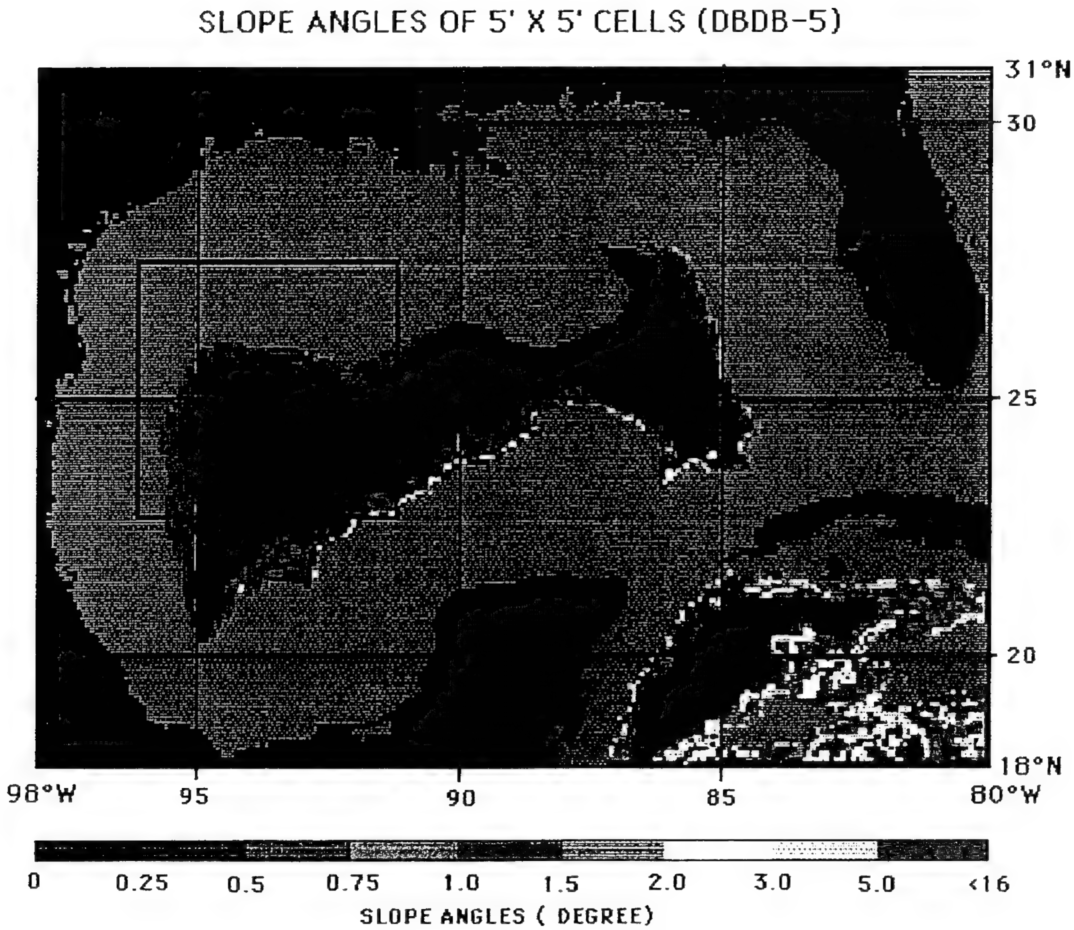


Figure 5.2.1-5. Seafloor slope angles in Gulf of Mexico (based on Fig. 5.2.1-2 bathymetry). Box shows area surrounding surrogate site.

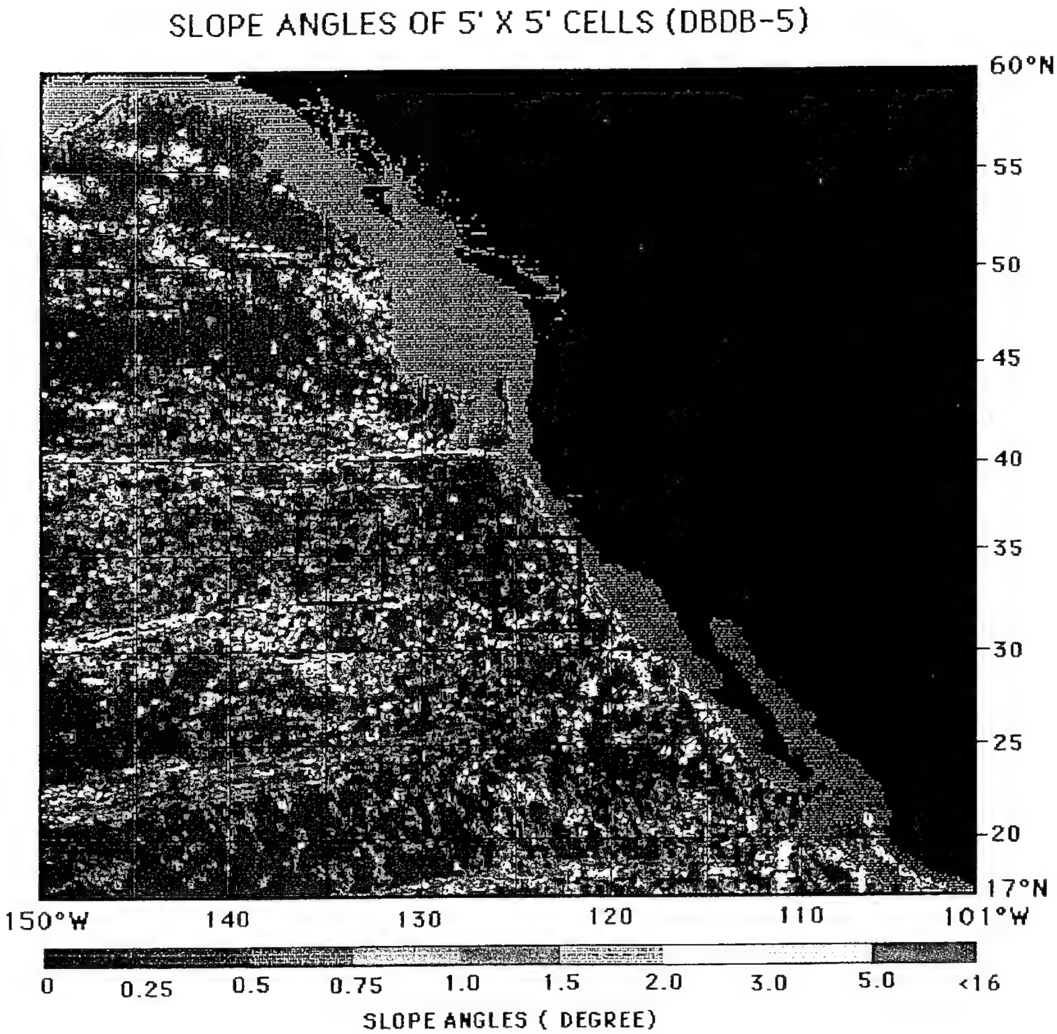


Figure 5.2.1-6. Seafloor slope angles in eastern Pacific (based on Fig. 5.2.1-3 bathymetry). 5° × 5° areas (boxes) surround surrogate sites.

degrees) will in almost all cases be considerably less than actual maximum seafloor slopes (which may be 10° to 20° or more on the slopes of seamounts or abyssal hills when measured by multibeam, although small escarpments seen by submersibles or deep-tow devices may be vertical cliffs). The low slopes computed from DBDB5 mainly reflect "low-pass filtering" inherent in gridding the data to a $5' \times 5'$ cell dimension. In rare cases DBDB5 slopes may be greater than actual if erroneous shallow soundings were reported in a relatively level area, producing a spurious DBDB5 high, which, when gridded, would produce spurious slopes on its flanks.

Local topographic relief computed from DBDB5 may also underestimate actual relief, although not to the extent slopes are underestimated. Gridding to $5' \times 5'$ will generally truncate the tops of high, steep ridges/seamounts or the bottoms of narrow, deep valleys (the latter are uncommon except near the mid-Oceanic Ridge axis, which is not being considered for waste isolation). In sparsely sounded regions, some ridges or seamounts — or at least their summits — may have been missed. For this project we computed maximum relief per $1° \times 1°$ cell. We also computed topographic "residuals" (relief) with respect to average depths for each cell (Figs. 5.2.1-7 through -9). Because the northeastern Pacific, northwestern Atlantic, and Gulf of Mexico have been relatively well-sounded at DBDB5 scales, we consider the residual topography and relief to be reasonably accurate, given the caveats discussed previously. Maximum DBDB5 depth and average depth per $1° \times 1°$ cell are likely to be more accurate still, probably ± a few hundred meters or better.

Whereas deep-water bathymetry is mapped acoustically, optic seafloor mapping (e.g., by lasers) has been attempted in very shallow water (< 50 m depth) or, in the abyss, by flying instruments a short distance above the seafloor. Optic imagery including bathymetry will be pressed into service for waste isolation site selection purposes if specific areas are selected for demonstration purposes.

While "acoustic bathymetry" is based on timing the round trip of an acoustic pulse, analysis of the entire time history of the returned pulse provides information about (a) the subbottom (generally nadir returns at relatively low frequencies, from tens of Hz to a few kHz) or (b) the backscatter properties (generally at grazing angles from 80° down to 10° or lower, and at relatively high frequencies, 5 to 15 kHz or even an order of magnitude higher for deep-towed systems). The former category of acoustics is often called seismoacoustic or seismic reflection profiling. The latter category is referred to as sidescan sonar, and yields plan view "backscatter imagery" which complements the bathymetry. "Seismic profiling" and "sidescan sonar" are not discussed in this chapter, but both will be pressed into service if and when specific waste isolation sites are investigated, both before and after material emplacement. These techniques are mentioned here because of their relationship to bathymetry—a relationship that in recent years has become steadily closer as sidescan sonars (such as SeaMARC II) have been "trained" to return bathymetry, even as hull-mounted bathymetric multibeam systems now also generate backscatter imagery of high quality. Today it is not uncommon for the same research vessel to collect swath bathymetry, low-frequency (ca. 50–200 Hz) seismic reflection, high-frequency (3.5 kHz) seismic reflection, and backscatter imagery. Because investigation of potential specific waste isolation sites would be conducted by such a multisystem vessel, the bathymetry collected around

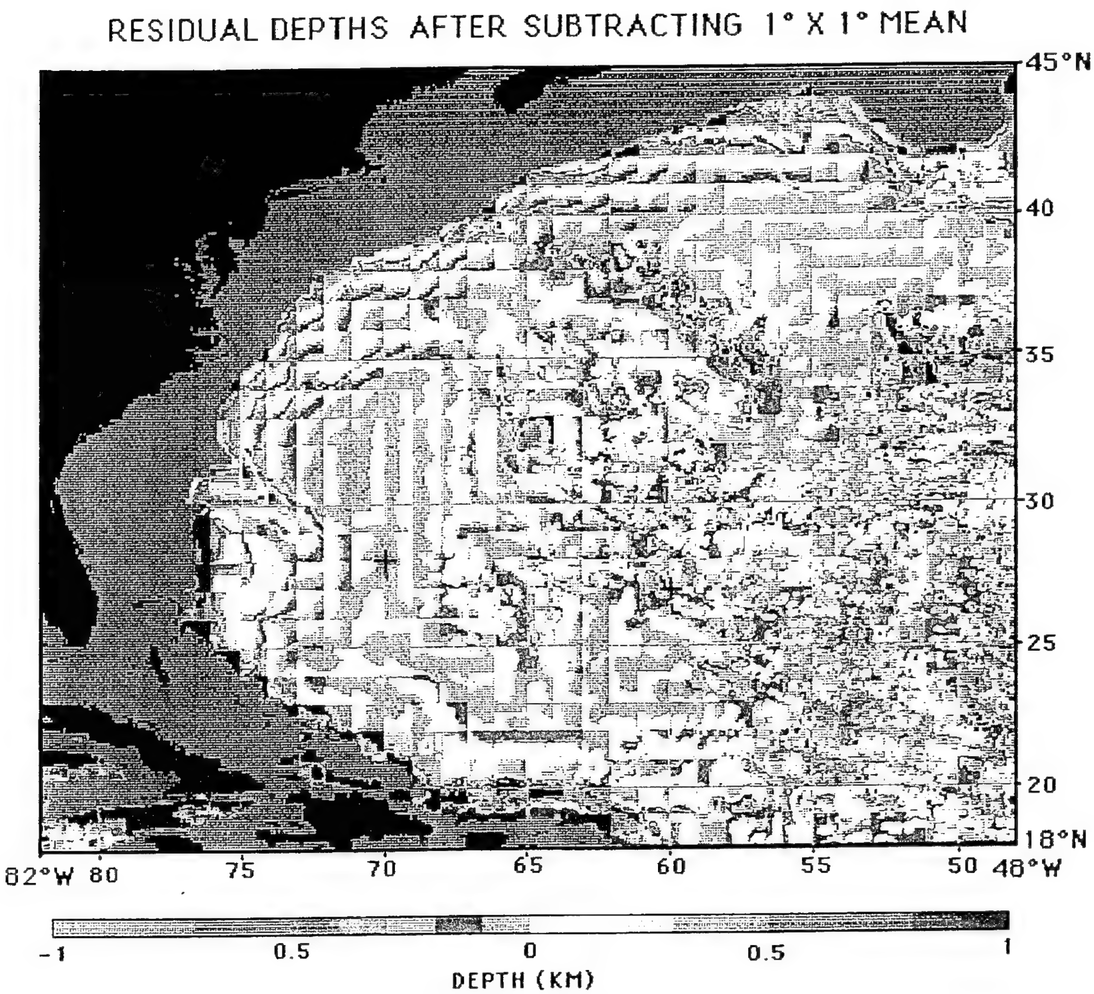


Figure 5.2.1-7. Residual depths for western north Atlantic (Fig. 5.2.1-1), computed by subtracting from each 5′ × 5′subcell-depth the mean DBDB-5 depths for the 1° × 1° cell within which the subcell is located. Crosses indicate surrogate sites. Color changes at 0.1 km (100 m) intervals. Cells or portions of cells less than 3000 m deep (gray areas) are excluded.

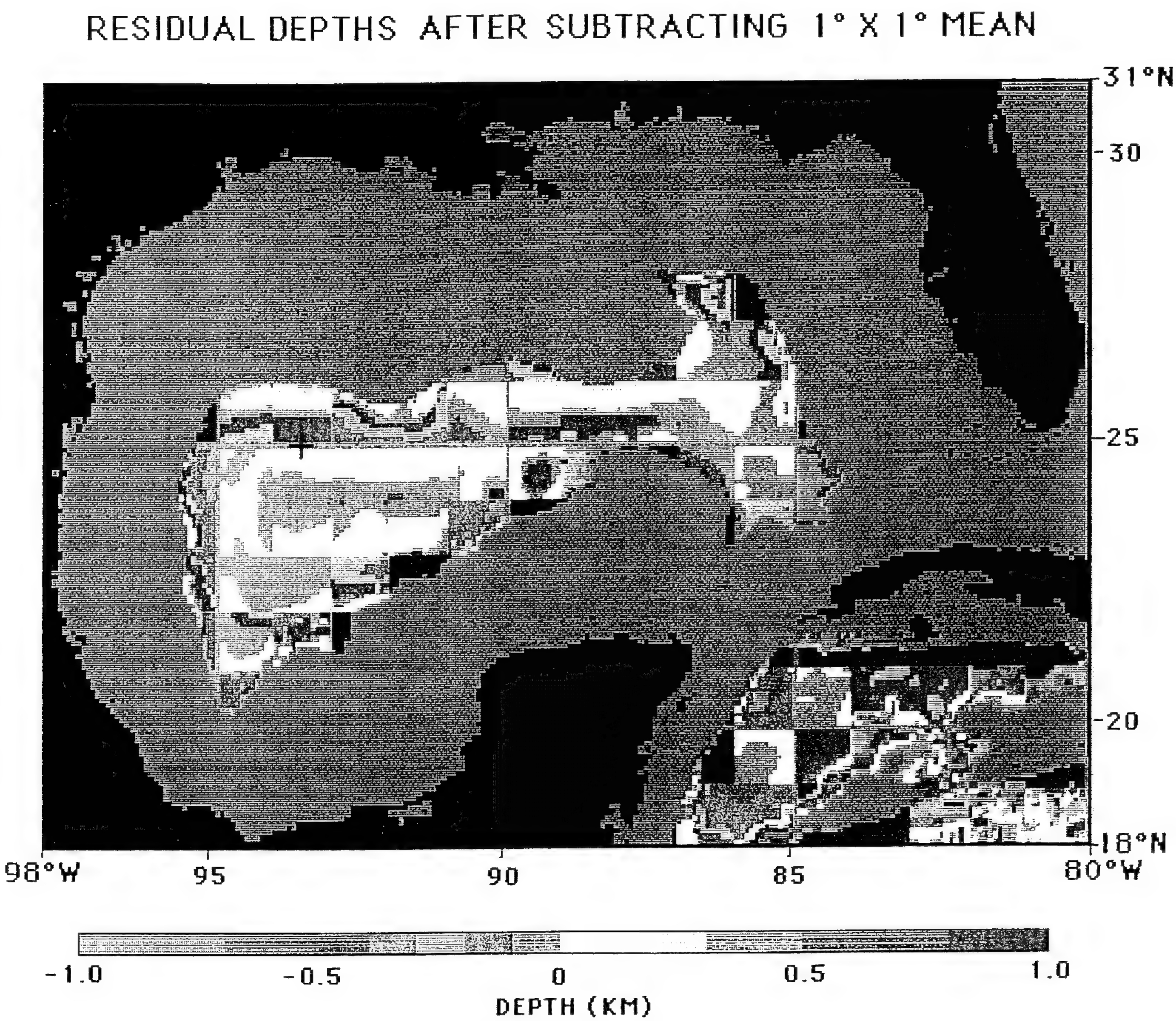


Figure 5.2.1-8. Residual depths for Gulf of Mexico (Fig. 5.2.1-2). Cross shows surrogate relocation site. Color changes at 0.1 km (100 m) intervals. Cells or portions of cells less than 3000 m deep (gray areas) are excluded.

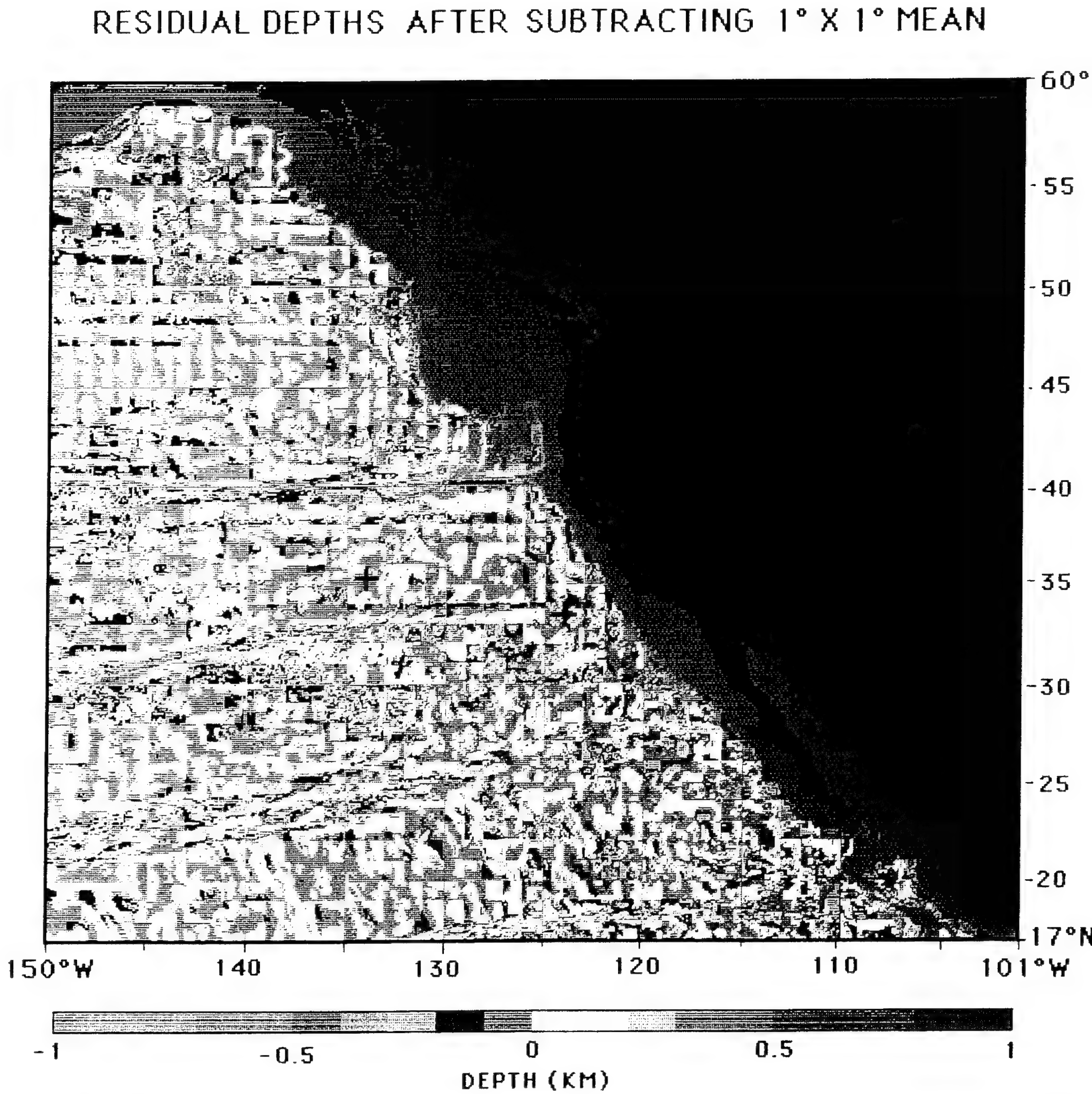


Figure 5.2.1-9. Residual depths for eastern Pacific (Fig. 5.2.1-3). Crosses show surrogate relocation sites. Color changes at 0.1 km (100 m) intervals. Cells or portions of cells less than 3000 m deep (gray areas) are excluded.

and over such sites would actually not be analyzed in isolation, but together with the other parameters.

5.2.1.3 DBDB5 Bathymetry

Parameters computed from the DBDB5 bathymetric gridded dataset are shown in Table 5.2.1-1 for the ocean areas surrounding each of the surrogate abyssal seafloor waste isolation sites. Columns 18 through 21 of this table also show the great-circle distance (km) from several major U.S. port cities to the centers of 1° x 1° cells surrounding the sites.

DBDB5 is based on contour charts of *uncorrected depth*, assuming a constant sound speed of 1500 m/s throughout the oceans. That is, geographic and vertical sound speed variability have not been taken into account to compute water depth from the round-trip travel time actually measured by echo-sounding systems. This computation was for many years (starting 1939) done by use of the so-called "Matthews Tables" (used in DBDB5) which in recent years have been replaced by a slight refinement called the "Carter Tables" (Carter 1980). Many bathymetric charts and databases (e.g., DBDB5) through the years have and continue to be produced simply in units of round-trip travel time, usually assuming a constant sound speed of 1500 m/s throughout the oceans. The Atlantic bathymetric chart of Tucholke et al. (1986) is based on DBDB5, but with the Carter corrections applied. The difference between corrected (Matthews or Carter Tables) and "uncorrected" bathymetric charts can range up to several hundred meters at abyssal depths. While such differences have no practical relevance in the portrayal of seafloor topography or its geomorphologic interpretation, the corrected (actual) water depth is obviously important for abyssal waste isolation when containers, vehicles, or pipe strings descend from the sea surface to the seafloor. Once the corrected depth is precisely known by detailed echosounding, the true depth is not likely to differ by more than 5–10 m at most due to meteorological and tidal effects and remaining uncertainties in the sound speed structure.

Interpolation of the DBDB5 database yields the following uncorrected and (corrected) water depths at the abyssal waste isolation surrogate sites: Atlantic-1, 5438 (5498) m; Atlantic-2, 6001 (6082) m; Gulf of Mexico, 3612 (3622) m; Pacific-1, 4387 (4381) m; and Pacific-2, 5205 (5219) m. Other sites in the general vicinity of the surrogate sites will have the same or very similar corrections. The best-fitting slopes at these five sites are 0.038°, 0.110°, 0.011°, 0.855°, and 0.0049°, respectively. Only the Pacific-1 site exhibits a "high" slope (by DBDB5) standards), suggesting the presence of topographic relief in the vicinity of this surrogate site. Detailed bathymetric data are needed to define the actual local slopes at any site.

Interpretation of regional charts of bathymetry, topographic slope, and residual bathymetry (upon removal of 1° x 1° averages) for the ocean areas considered for abyssal waste isolation (Figs. 5.2.1-1 through -9) follow. Atlantic-1 is located on the Hatteras Abyssal Plain between the U.S. margin to the west, and the southern Bermuda Rise to the east (Fig. 5.2.1-1). Atlantic-2 is located in the deep area between the Bermuda Rise and the mid-Atlantic Ridge (lower right in Fig. 5.2.1-1). The Gulf of Mexico site is located on the nearly flat Sigsbee Abyssal Plain, an area where sediments are many kilometers thick. This environment

Table 5.2.1-1. Bathymetric and geographic statistics (all depths in meters) computed from DBDB-5 for 1° x 1° surrounding surrogate abyssal waste isolation sites.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	Pacific	#1															
984	34.5	-125.5	4711	4329	-5.2	0.1	4613	4600	68	144	4594	66	144	144	0.0	1.6	1478.6
985	33.5	-125.5	4882	4155	-75.8	0.1	4406	4463	117	144	4460	102	143	143	0.0	2.5	1588.2
986	32.5	-125.5	4781	3689	-107.9	0.1	4398	4399	103	144	4387	101	142	142	0.0	5.4	1697.9
1016	34.5	-124.5	4599	3293	12.5	0.2	4400	4374	177	144	4367	154	144	144	0.0	5.2	1466.0
1017	33.5	-124.5	4765	3883	-16.2	0.1	4395	4375	132	144	4365	97	144	144	0.0	4.5	1576.3
1018	32.5	-124.5	4429	4023	-32.9	0.1	4394	4356	73	144	4343	70	136	136	0.0	1.9	1686.6
1041	34.5	-123.5	4421	3992	68.3	0.2	4232	4246	112	144	4256	107	144	144	0.0	1.8	1458.1
1042	33.5	-123.5	4756	3646	-49.1	0.2	4305	4254	170	144	4245	135	144	144	0.0	3.4	1568.8
1043	32.5	-123.5	4394	3809	-83.6	0.0	4219	4210	98	144	4207	78	141	141	0.0	2.3	1679.5
1064	34.5	-122.5	4307	3536	25.4	0.1	4081	4076	95	144	4068	103	144	144	0.0	3.8	1454.9
1065	33.5	-122.5	4379	3573	8.0	0.2	4190	4128	151	144	4107	141	144	144	0.0	2.6	1565.8
1066	32.5	-122.5	4283	3521	18.3	0.1	4154	4111	113	144	4108	89	144	144	0.0	2.6	1676.7
	Pacific	#2															
659	35.5	-134.5	5211	4871	97.5	0.1	5190	5144	76	144	5150	61	143	143	0.0	1.6	1679.8
660	34.5	-134.5	5384	5093	-127.8	0.0	5200	5202	37	144	5200	34	143	143	0.0	1.1	1773.7
697	35.5	-133.5	5212	4830	16.4	0.0	5194	5162	65	144	5156	54	143	143	0.0	1.8	1631.5
698	34.5	-133.5	5205	4920	-22.2	0.0	5171	5153	52	144	5148	46	144	144	0.0	1.3	1727.4
	North	Atlantic	#1														
181	28.5	-70.5	5422	5314	150.5	0.0	5363	5362	23	144	5366	23	144	144	0.0	0.1	1390.9
182	27.5	-70.5	5456	5355	134.9	0.0	5429	5422	22	144	5425	20	144	144	0.0	0.1	1499.3
205	28.5	-69.5	5434	5238	14.6	0.1	5346	5340	51	144	5335	55	144	144	0.0	0.3	1414.8
206	27.5	-69.5	5459	5146	-5.0	0.2	5399	5358	96	144	5347	98	144	144	0.0	0.6	1521.7
	North	Atlantic	#2														
419	27.5	-61.5	6175	5333	144.1	0.2	5858	5856	159	144	5864	133	143	143	0.0	2.7	1860.7
420	26.5	-61.5	6183	5614	-117.3	0.1	5877	5884	116	144	5887	113	144	144	0.0	1.6	1952.6
446	27.5	-60.5	- 6207	5249	84.6	0.1	5993	5974	179	144	5968	168	144	144	0.0	3.4	1918.6
447	26.5	-60.5	_6196	5610	-29.3	0.1	6007	–5993	174	144	5987	160	144	144	0.0	2.9	2008.4
	Gulf of	Mexico															
33	25.5	-94.5	3629	2596	107.3	0.4	3420	3376	218	144	3413	191	144	144	0.0	1.5	659.9
34	24.5	-94.5	3704	3581	157.3	0.0	3626	3629	19	144	3632	20	141	141	0.0	0.2	747.5
45	25.5	-93.5	3629	2971	85.4	0.3	3477	3443	166	144	3461	156	144	144	0.0	2.1	599.0
46	24.5	-93.5	3739	3605	79.3	0.1	3640	3656	42	144	3661	43	143	143	0.0	0.2	693.8
57	25.5	-92.5	3601	2207	70.5	0.6	3307	3172	385	144	3214	339	144	144	0.1	3.2	549.1
58	24.5	-92.5	3724	3554	77.9	0.1	3623	3637	36	144	3642	37	142	142	0.0	0.3	650.8

ıted from DBDB-5 for 1° x 1° squares in the areas

3	14	15	16	17	18	19	20	21
6	144	144	0.0	1.6	1478.6	460.8	673.8	
2	143	143	0.0	2.5	1588.2	554.3	673.2	
1	142	142	0.0	5.4	1697.9	653.2	690.5	
4	144	144	0.0	5.2	1466.0	413.0	582.4	
7	144	144	0.0	4.5	1576.3	514.7	580.5	
0	136	136	0.0	1.9	1686.6	619.6	599.4	
7	144	144	0.0	1.8	1458.1	380.7	491.4	
5	144	144	0.0	3.4	1568.8	488.9	487.9	
8	141	141	0.0	2.3	1679.5	598.0	509.1	
3	144	144	0.0	3.8	1454.9	368.1	400.8	
1	144	144	0.0	2.6	1565.8	479.0	395.3	
9	144	144	0.0	2.6	1676.7	589.9	420.1	
1	143	143	0.0	1.6	1679.8	1109.7	1501.0	
4	143	143	0.0	1.1	1773.7	1146.9	1499.8	
4	143	143	0.0	1.8	1631.5	1023.1	1410.5	
6	144	144	0.0	1.3	1727.4	1062.2	1408.0	
3	144	144	0.0	0.1	1390.9	1073.4	1019.4	1005.6
0	144	144	0.0	0.1	1499.3	1171.6	1079.1	982.5
5	144	144	0.0	0.3	1414.8	1123.6	1105.0	1100.5
8	144	144	0.0	0.6	1521.7	1218.2	1161.1	1080.2
3	143	143	0.0	2.7	1860.7	1735.2	1865.6	1868.2
3	144	144	0.0	1.6	1952.6	1808.9	1911.1	1868.4
8	144	144	0.0	3.4	1918.6	1811.3	1956.9	1967.0
0	144	144	0.0	2.9	2008.4	1882.7	2001.2	1968.0
1	144	144	0.0	1.5	659.9	423.8		
0	141	141	0.0	0.2	747.5	534.4		
6	144	144	0.0	2.1	599.0	441.5		
3	143	143	0.0	0.2	693.8	548.7		
9	144	144	0.1	3.2	549.1	479.4		
7	142	142	0.0	0.3	650.8	579.8		

Descriptions of column contents

Column #	Description Data
1	1^0 x 1^0 cell number, see section 3.3.2, Site Selection Mc
2	latitude of cell centers, ^{0}N
3	longitude of cell centers, ^{0}W
4	maximum seafloor depths
5	minimum seafloor depths
6	strike (azimuth angle) of best-fitting (least square) plaı measured in degrees, clockwise positive from North
7	slope angle of best-fitting plane
8	median cell depth of 144 5′ x 5′ subcells in each 1^0 x 1^0
9	mean seafloor depth
10	standard deviation of subcell seafloor depth from mean
11	total number of counted subcells in 1^0 x 1^0 cell
12	mean depth of all subcells with slopes less than 0.25^0
13	standard deviation of subcell depths from mean depth
14	number of subcells for which slope angle is less than 0.2
15	number of subcells for which azimuth and slope were cc
16	minimum subcell slope per 1^0 x 1^0 cell
17	maximum subcell slope per 1^0 x 1^0 cell
18	great circle distances from Atlantic cell centers to Nev 74^{0}01′W,from Pacific cells to Seattle (47^0 36′N, 122^0 2 Mexico cell centers to New Orleans (29^0 57′N, 90^0 03′\
19	similar to 18, with distances computed from Norfolk San Francisco (37^0 49′N, 122^0 25′W) and Galveston (2
20	similar to 18, with distances computed from Miami (25^0

Descriptions of column contents

Column #	Description Data
1	$1^0 \times 1^0$ cell number, see section 3.3.2, Site Selection Model, Description.
2	latitude of cell centers, ^{0}N
3	longitude of cell centers, ^{0}W
4	maximum seafloor depths
5	minimum seafloor depths
6	strike (azimuth angle) of best-fitting (least square) planar surface to cell data measured in degrees, clockwise positive from North
7	slope angle of best-fitting plane
8	median cell depth of 144 5′ x 5′ subcells in each $1^0 \times 1^0$ cell
9	mean seafloor depth
10	standard deviation of subcell seafloor depth from mean depth in cell
11	total number of counted subcells in $1^0 \times 1^0$ cell
12	mean depth of all subcells with slopes less than 0.25^0
13	standard deviation of subcell depths from mean depth
14	number of subcells for which slope angle is less than 0.25^0
15	number of subcells for which azimuth and slope were computed
16	minimum subcell slope per $1^0 \times 1^0$ cell
17	maximum subcell slope per $1^0 \times 1^0$ cell
18	great circle distances from Atlantic cell centers to New York City ($40^0$42′N, $74^0$01′W,from Pacific cells to Seattle (47^0 36′N, 122^0 20′W) and from Gulf of Mexico cell centers to New Orleans (29^0 57′N, 90^0 03′W)
19	similar to 18, with distances computed from Norfolk (36^0 51′ N, 76^0 01′W) San Francisco (37^0 49′N, 122^0 25′W) and Galveston (29^0 19′N, 94^0 47′W)
20	similar to 18, with distances computed from Miami (25^0 47′N, 80^0 11′W)

is similar to that around Atlantic-1, where sediments are not as thick as below the Sigsbee plain, but still thick enough to bury the original oceanic crustal topography such as expressed in the bathymetry farther east in the Atlantic. In the eastern Pacific, sediment cover is relatively thin (a few hundred meters or less) even rather close to the continental margin. Thus the topography (Fig. 5.2.1-3) is primarily a function of crustal age (younger seafloor is shallower), and major depth changes across east-west trending fracture zones simply reflect the past geometry of the East Pacific Rise.

Representation of seafloor slopes (Figs. 5.2.1-4 through -6) shows level areas in blue. Subcells ($5' \times 5'$) with slopes steeper than 2° are shown in yellow-orange-red, and generally are associated with seamounts and fracture zones, locally also abyssal hill topography, in the Pacific and in the Atlantic generally east of Atlantic-1. As noted earlier, the actual slopes associated with these colors are locally steeper (see next section). Some slopes of yellow and higher are also present along parts of the continental margin, for example the Atlantic margin from 30° south, and along the southern margin of the Gulf of Mexico (Fig. 5.2.1-5). Carbonate (limestone) escarpments account for these steep slopes in the gulf and, between 20°N and 30°N, in the Atlantic (Fig. 5.2.1-4). (Steep slopes south of 20°N reflect tectonic processes along the margin between the North American and Caribbean plates.)

Residual depths (Figs. 5.2.1-7 through -9) are straightforward in interpretation. The $1° \times 1°$ cells covering abyssal plains or other nearly level areas are about 50% yellow and 50% green in color. Cells occupying continental slopes show a uniform "rainbow" of colors, while cells containing shallow regions show more strongly negative depth anomalies in the deeper portions of the cell. Areas of complex local topography (seamounts, mid-Oceanic Ridge flanks, etc.) tend to show a large range of colors (in some cases the entire 2-km color range) in each cell. This type of topography is not present in the modern Gulf of Mexico (Fig. 5.2.1-8). Although not apparent in the DBDB5 data around Atlantic-2 and Pacific-1, local flat areas suitable for abyssal waste isolation are present at these sites as well (see next section).

Figures 5.2.1-10 through -14 are "blowups" from DBDB5 of depth and slopes for $5° \times 5°$ regions around the surrogate sites. The $5° \times 5°$ regions are outlined as black squares on Figures 5.2.1-4 through -6. The different "size" of these boxes reflects the different scales of enlargement for the different ocean areas in Figs. 5.2.1-1 through -9. By contrast Figs. 5.2.1-10 through -14 are all shown at the same scale. The enlargement in these figures is great enough to show each $5' \times 5'$ subcell as a separate box except where the seafloor is level or uniformly sloping. The geologic significance of the bathymetric slope and the limitations inherent in DBDB5 based computations has been summarized above.

5.2.1.4 Detailed Bathymetry

Detailed U.S. Navy multibeam-based contour sheets were examined for $2° \times 2°$ boxes centered roughly on the surrogate abyssal waste isolation sites for the Atlantic and Pacific surrogate sites. No such data were available around the Gulf of Mexico site. The area 27°–29°N, 69°–71°W, containing Atlantic-1, was found to be ca. 50% covered by multibeam

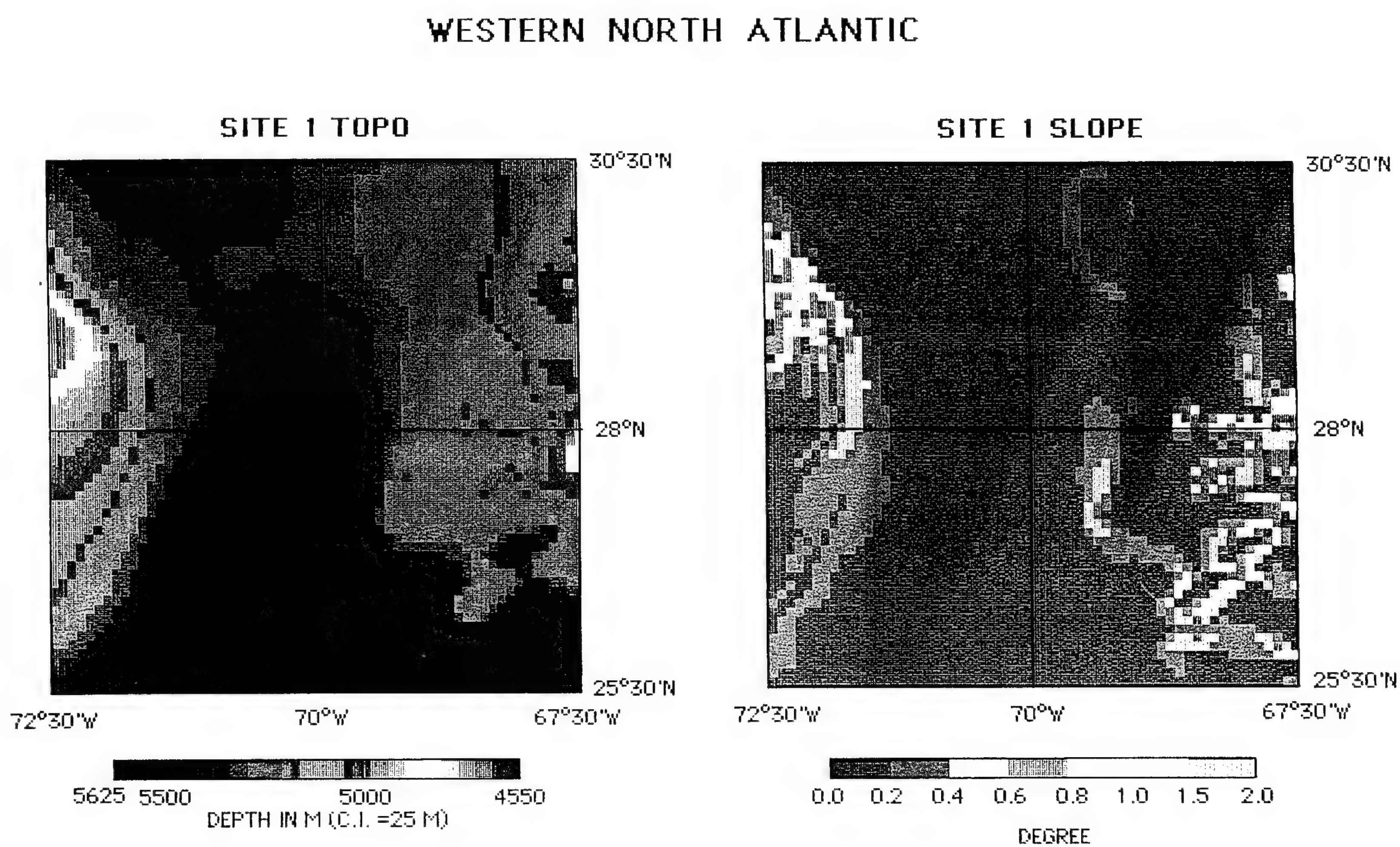


Figure 5.2.1-10. Depths and slopes (from DBDB-5) for 5° × 5° area surrounding Atlantic surrogate site 1. See Figs. 5.2.1-1 and -4 for location.

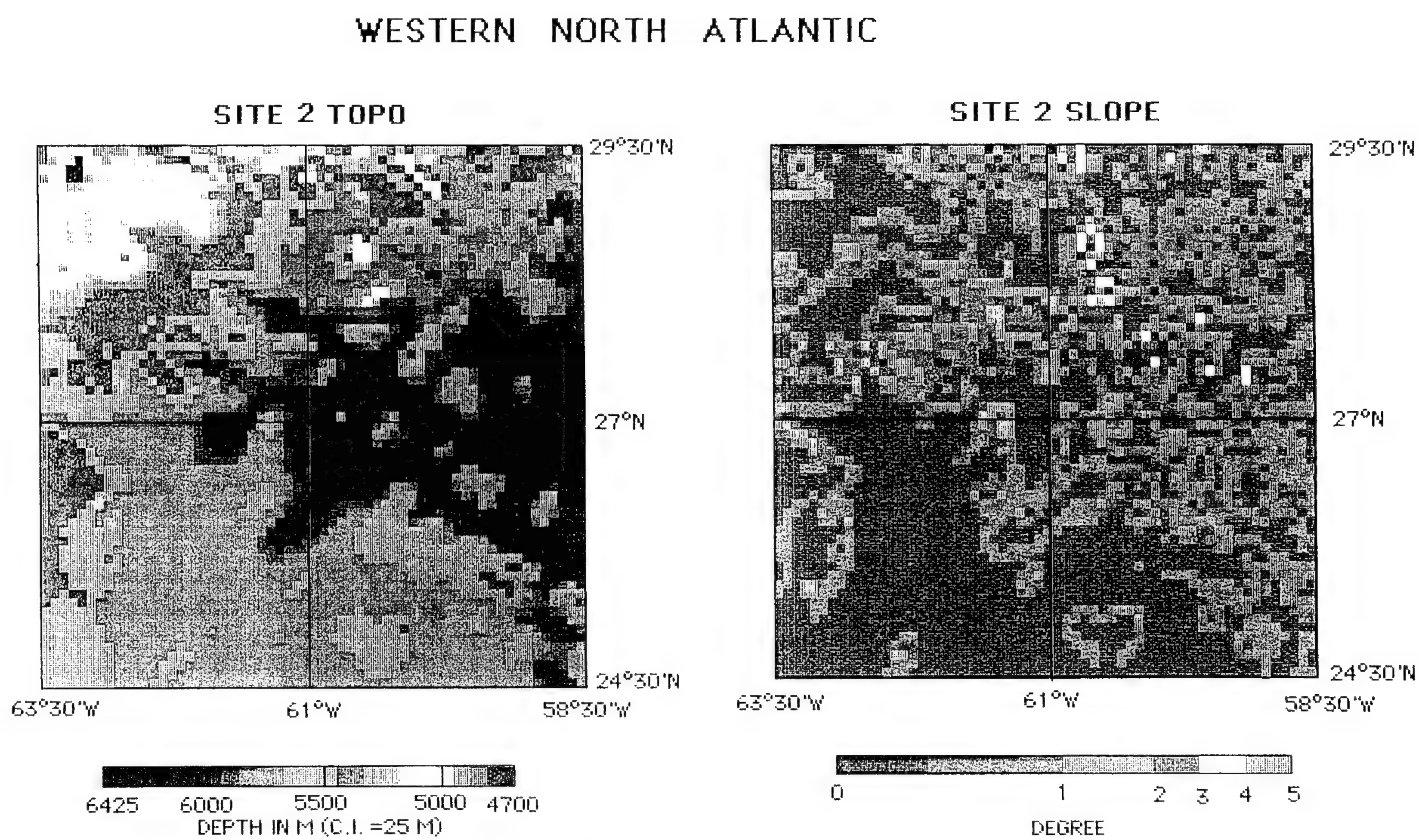


Figure 5.2.1-11. Depths and slopes (from DBDB-5) for 5° × 5° area surrounding Atlantic surrogate site 2. See Figs. 5.2.1-1 and -4 for location.

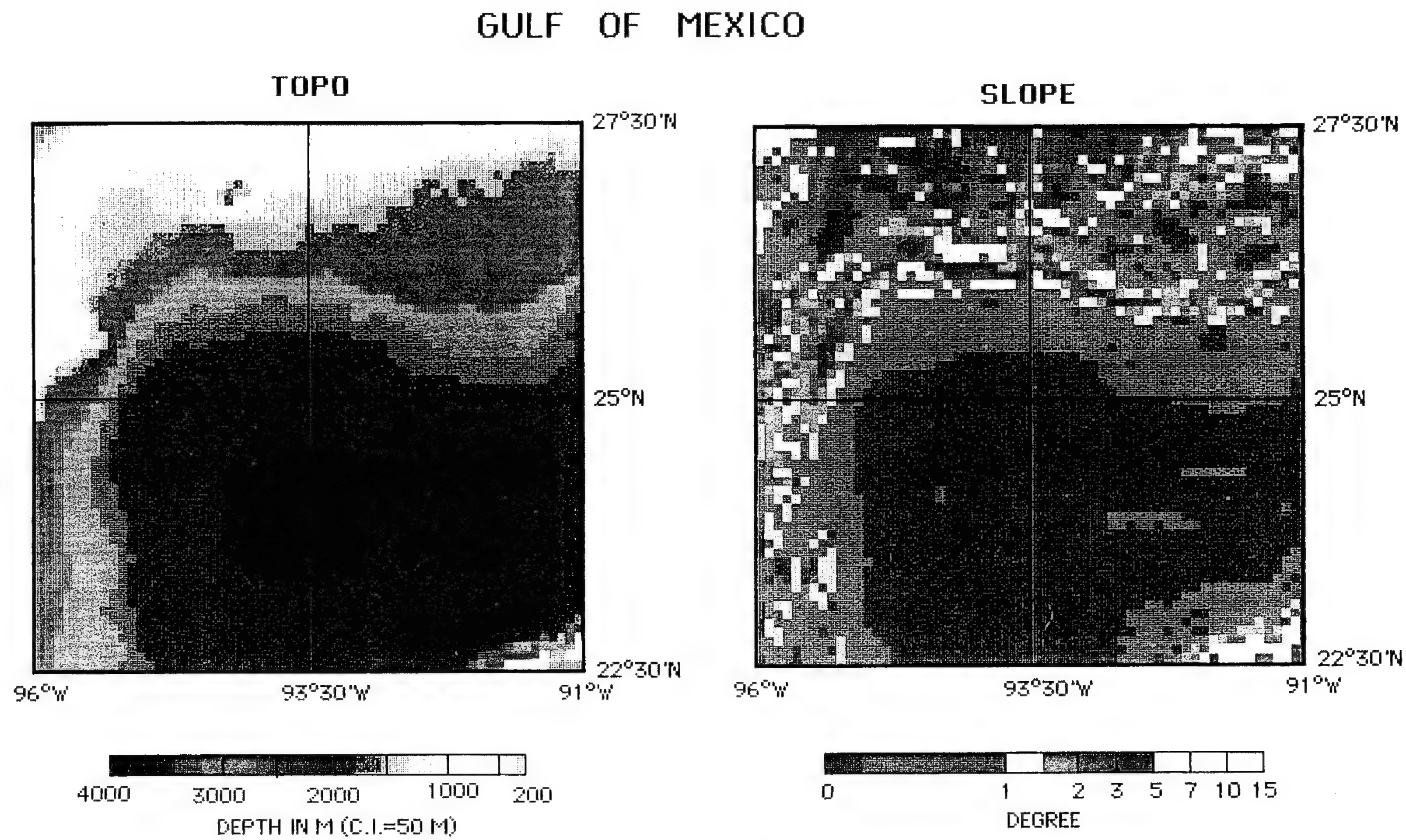


Figure 5.2.1-12. Depths and slopes (from DBDB-5) for 5° × 5° area surrounding surrogate site in Gulf of Mexico. See Figs. 5.2.1-2 and -5 for location.

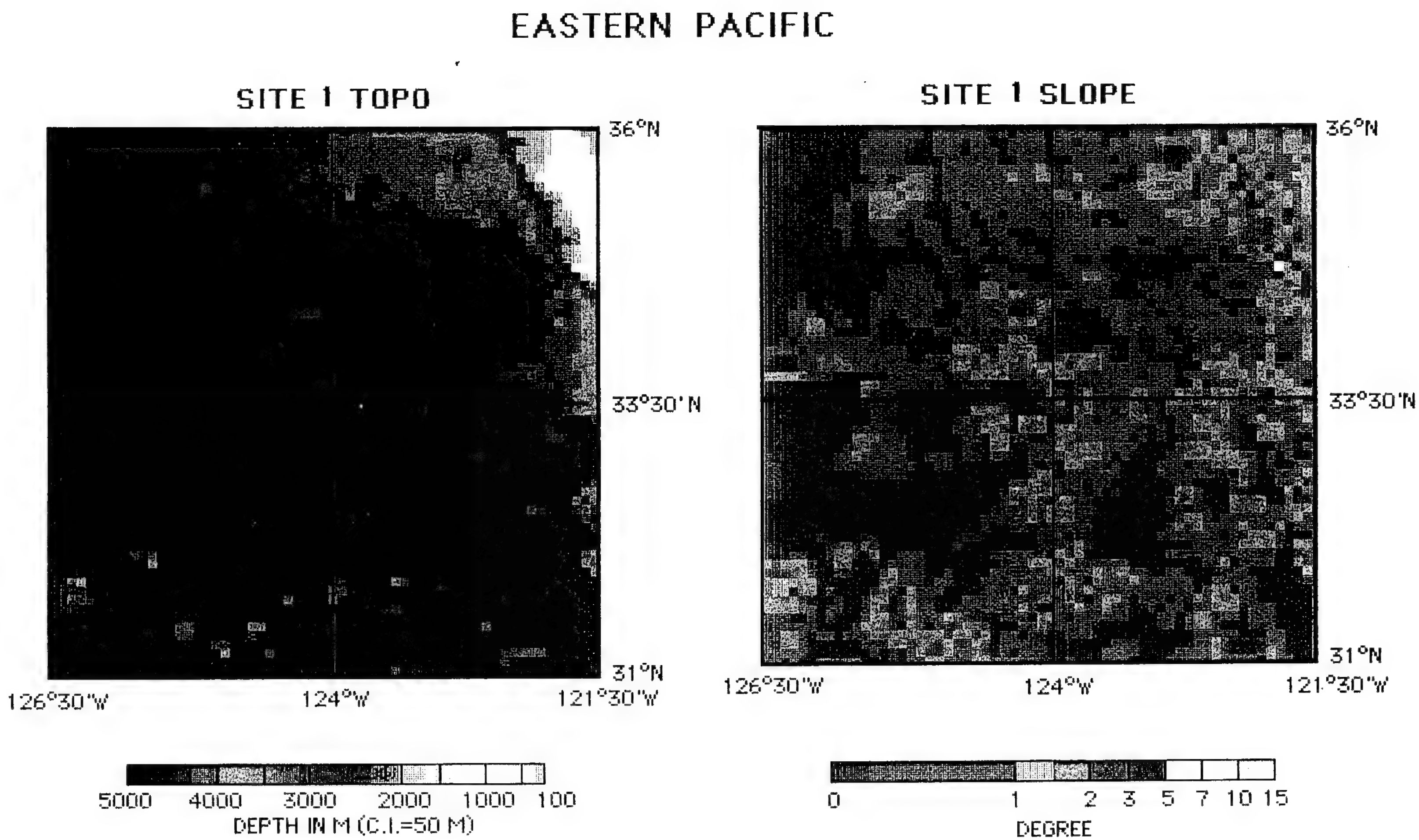


Figure 5.2.1-13. Depths and slopes (from DBDB-5) for 5° × 5° area surrounding surrogate site 1 in eastern Pacific. See Figs. 5.2.1-3 and -6 for location

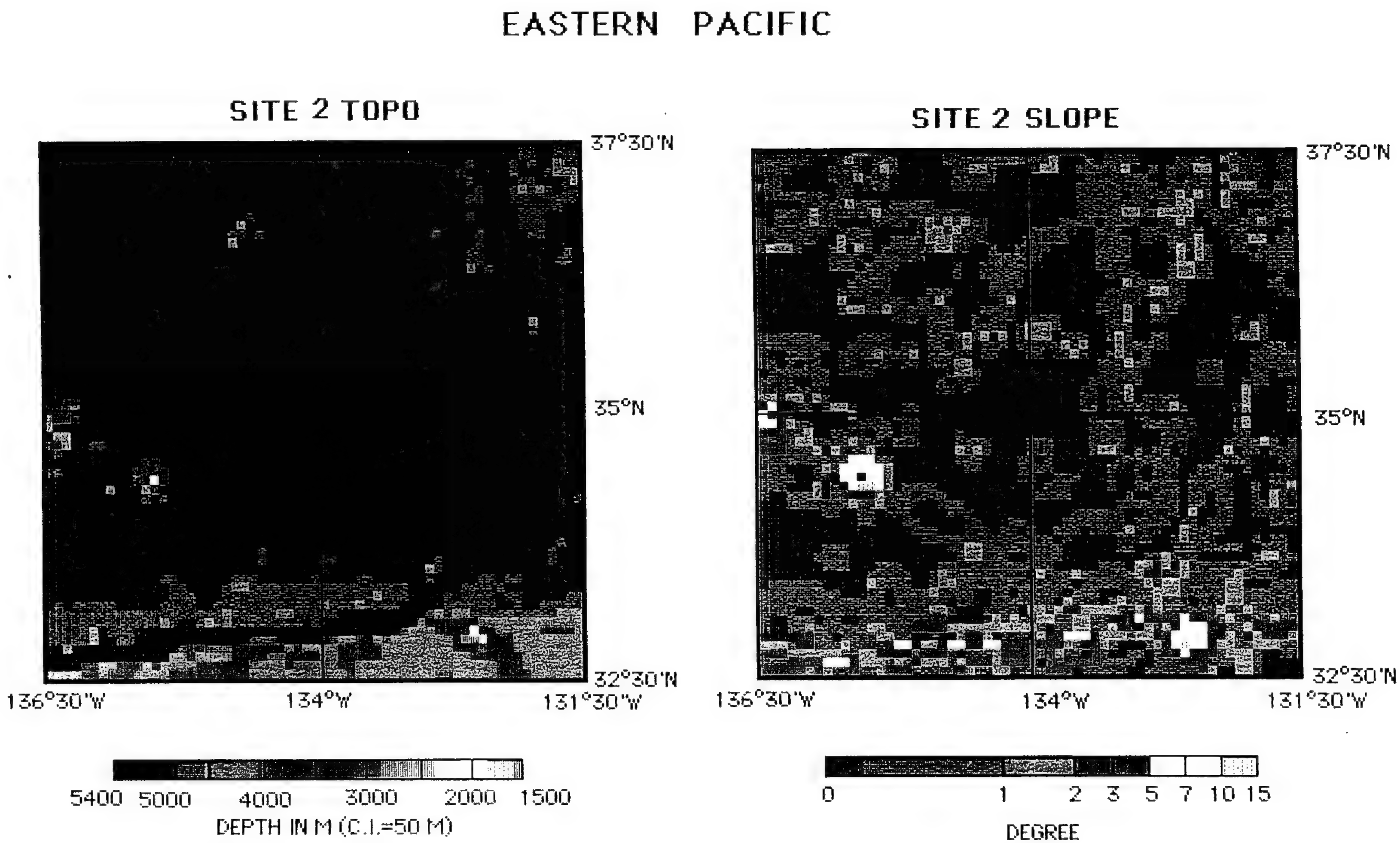


Figure 5.2.1-14. Depths and slopes (from DBDB-5) for 5° × 5° area surrounding surrogate site 2 in eastern Pacific. See Figs. 5.2.1-3 and -6 for location.

swaths. The corresponding figures for Atlantic-2 (26°–28°N, 60°–62°W), Pacific-1 (32°45′–35°15′N, 125°15′–122°45′W), and Pacific-2 (34°–36°N, 133°–135°W) are ca. 50%, 30%, and 25% coverage, respectively.

The area surrounding Atlantic-1 can be roughly divided into the Hatteras Abyssal Plain area west of 69°50′W, and the lower flanks of the Bermuda Rise, east of 69°50′W. Contours in the western area show a featureless plain, the contours representing only system noise. Slopes are all < 6°, except on the flanks of one or possibly several small knolls ca. 2–4 km across, ca. 100 m high, where local slopes exceed 20°. (Some of the "knolls" may be artifacts.)

Eastward from 69°50′W, the flat seafloor grades into gently undulating topography comprising generally north to northwest trending, low, smooth ridges (probably abyssal ridges deeply buried by draped hemipelagic sediments). The ridges are typically 20–50 km long, 10 km apart, and exhibit a relief of 50–300 m. Just south of the northeast corner of the area, the relief is more complex, with northeast and east-west topographic trends possibly associated with a buried fracture zone. Slopes east of 69°50′W are mostly <6° but locally reach 6°–10° in the area of the north to northwest trending ridges. Complex, dissected-looking, seamount-like highs are located near 28°25′N, 69°45′W and 28°30′N, 69°10′W. These features rise ca. 500 m above their 10 km wide bases and exhibit slopes >6°, locally >20°.

The seafloor around Atlantic-2 is dominated by northeast-trending abyssal hill topography, with ridges 10–50 km long, 1–5 km wide, 4–10 km apart, and 400–1000 m in relief. Major fracture valleys and ridges trending northwest cross 60°W between 26°05′N and 27°10′N, disappearing and/or petering out in the central and western part of the area, where sediments are presumably thicker. Circular, volcanic knolls/seamounts are scattered across the region and are locally numerous, ranging from 5 km across, 800 m high down to 300–1000 m in diameter, < 100 m high. Abyssal plains and fracture zone valley floors, as well as volcanic knoll summits, are flat. Slopes > 6°, in many cases to > 20°, occur on the flanks of abyssal hills/ridges, fracture zone ridges and valleys, and volcanic knolls. The largest level areas are up to 20 km across. Long fracture zone valley floors are also flat and typically 10 km wide. Most or all of these flat areas are parts of the distal Nares Abyssal Plain system.

The area around Pacific-2, the westernmost site, exhibits classic "Pacific" terrain. The area is dominated by north-trending narrow abyssal hills (ridges) ca. 10–50 km long, up to a few hundred meters high, 1–2 km wide, and spaced 3–10 km apart. Circular volcanic knolls as small as 200 m across, the largest being 10 km in base diameter and 500–1000 m high, are scattered across the entire area. No significant fracture zone topography is present. Flank slopes on ridges and knolls commonly range from > 6° to 15°, locally to > 20°. The widest intermontane valleys are only 4–5 km wide, although larger flat areas 20 km across and extending beyond the examined area are centered around 35°42′N, 134°22′W. None of the flat areas in this region are as flat as the Atlantic-1 and -2 abyssal plains, i.e., so flat that only system noise appears in the contours.

The area around Pacific-1 is, in its southwest quadrant, very similar to Pacific-2. However, north of 34°N and east of 123°30′W the seafloor is relatively smooth, with only isolated protruding abyssal hills (ridges) and small seamounts, the largest 10 km across and

500 m high. The south-central to central part of the area is complex, with locally rough topography with variably trending (northwest, northeast, and north) abyssal ridges. This complex province terminates in the north against a complex, east-west trending fracture zone, with prominent east-west escarpments, in the interval 33°40′–33°55′N. A relatively flat area (slopes <1:500 to 1:250) is located between 34°05′ and 34°30′N, and between 124°15′ and 125°W. Other relatively smooth areas to the east and south appear to be sediment-covered, low-relief (<100 m) abyssal ridges with slopes of <6°. As in other areas where volcano-tectonic crustal topography is evident in the bathymetry (around Pacific-2 and Atlantic-2, and east of Atlantic-1), flank slopes on volcanic knolls/seamounts, abyssal hills (ridges), and fracture zone topography exceeds 6° in many places, and locally even exceeds 20° in slope. As discussed elsewhere in this section, such steep slopes are not evident (resolved) in DBDB5 scale bathymetric datasets. Such slopes may consist of exposed altered volcanic rock, the hemipelagic sediments deposited on them having slumped off at infrequent intervals, and deposited in the nearby intermontane valleys.

5.2.1.5 Predicting Benthic Biomass from Bathymetry

Any relevant parameter that exhibits an empirical or theoretical dependence on water depth — whether in a given area or globally — can be "predicted" and mapped by use of gridded bathymetric databases. The errors inherent in such predictions will depend on the errors (including those produced by smoothing/filtering) in the bathymetric dataset, as well as the errors (including dependence on nonbathymetric variables) in the relationship between the parameter of interest and the bathymetry. In this section we use G. Rowe's empirical relation between biomass and water depth to predict biomass (see Section 2.4.3, **Deep-Sea Biomass and Related Processes**).

Rowe's relation expresses a logarithmic decrease of living biomass (vertically integrated in the sediment, and expressed as grams living matter, exclusive of bacteria, per square meter seafloor) with increasing water depth. We have combined Rowe's relation with DBDB5 to map "predicted" biomass (Figs. 5.1.2-15 through -17) and integrate total biomass in each ocean-depth interval (Figs. 5.2.1-18 and -19). Although the global dataset is sparse ($<10^3$ cores analyzed globally) and the scatter is large, a meaningful function can be derived for the biomass-water depth relation globally and for a few areas with sufficient data, primarily the Gulf of Mexico and the western North Atlantic. In general the living biomass is much greater on the continental shelves (>10 g/m^2) and declines to very low values (<1 g/m^2) at abyssal depths. To first order, this phenomenon results from the progressive consumption, by organisms in the water column, of organic matter settling to the seafloor from the photic zone, where primary production occurs.

Secondary effects, such as geographical and temporal variations in surface water organic productivity, account for some of the nondepth-related "noise" and could be accounted for in a follow-up study.

We have used Rowe's "global" relationship to generate biomass maps in the western North Atlantic and eastern North Pacific regions (Figs. 5.2.1-15 and 5.2.1-17). In the relatively well-sampled Gulf of Mexico, we used his fit specific to that area (Fig. 5.2.1-16). For

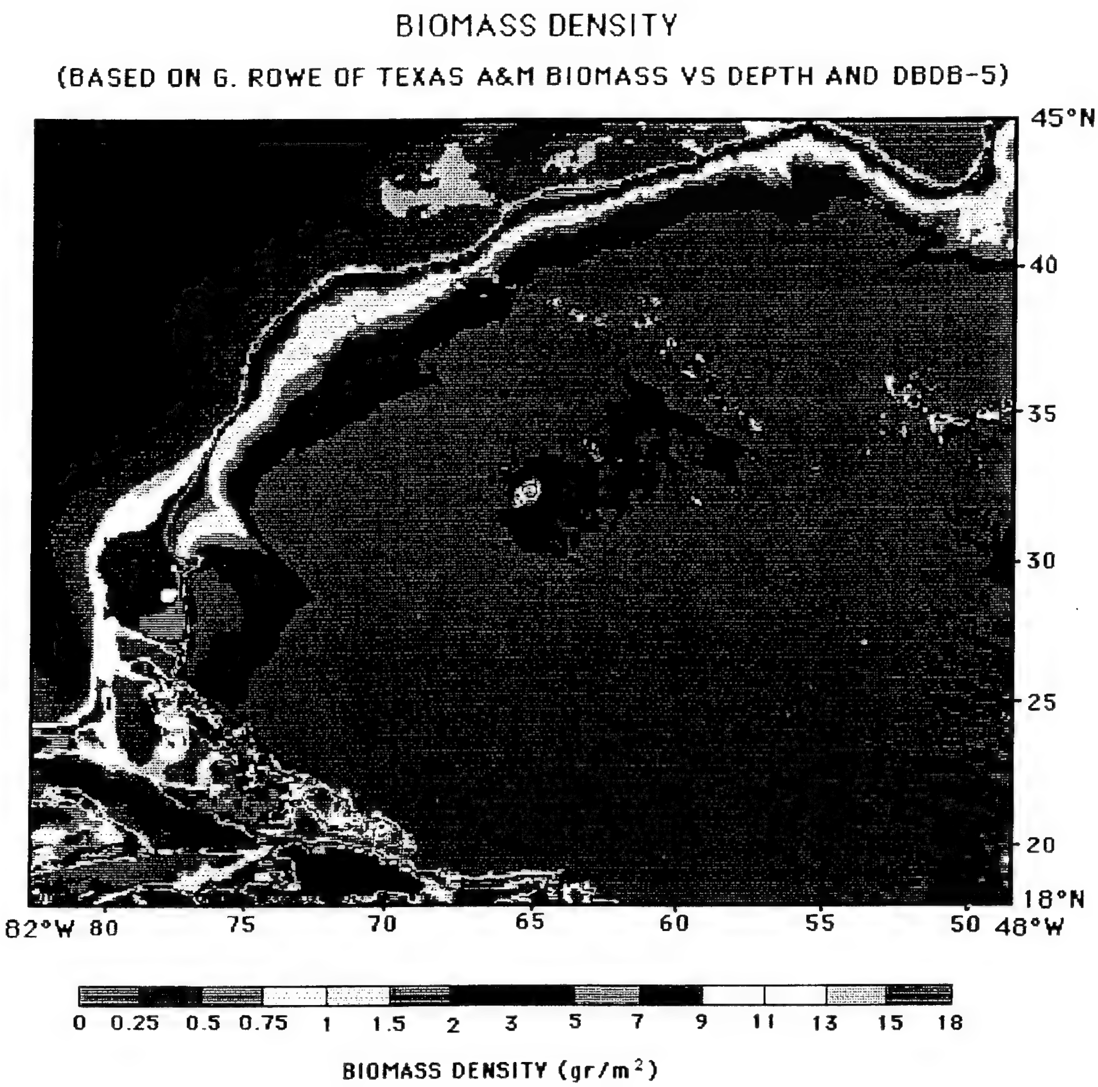


Figure 5.2.1-15. Living macrobenthos biomass density, grams organic carbon (g/m^2), for western North Atlantic. Based on DBDB-5 depths and global biomass-depth relation provided by G. Rowe (see section 2.4.3).

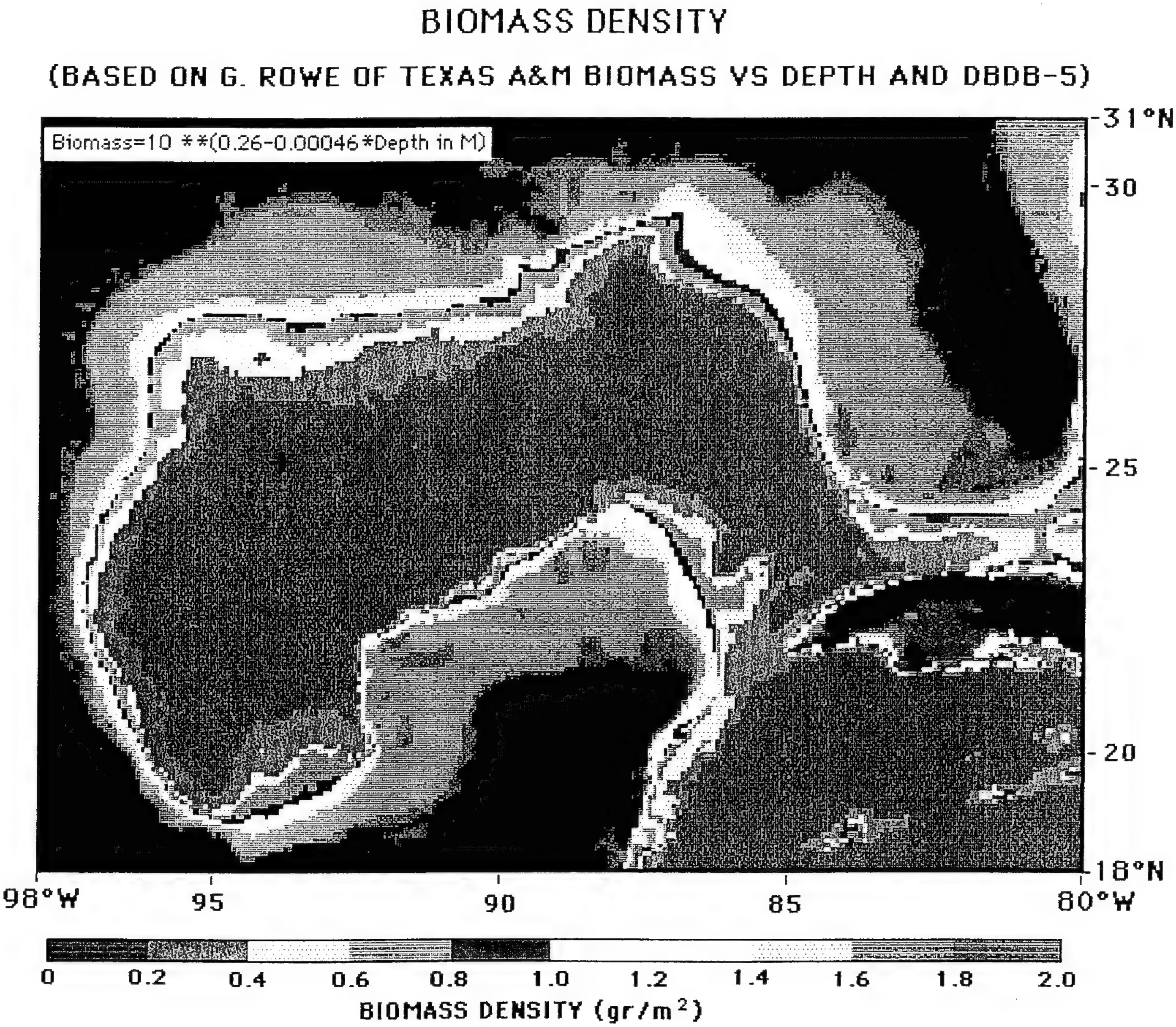


Figure 5.2.1-16. Living macrobenthos biomass density, grams organic carbon (g/m^2), for Gulf of Mexico. Based on DBDB-5 depths and global biomass-depth relation provided by G. Rowe (see section 2.4.3).

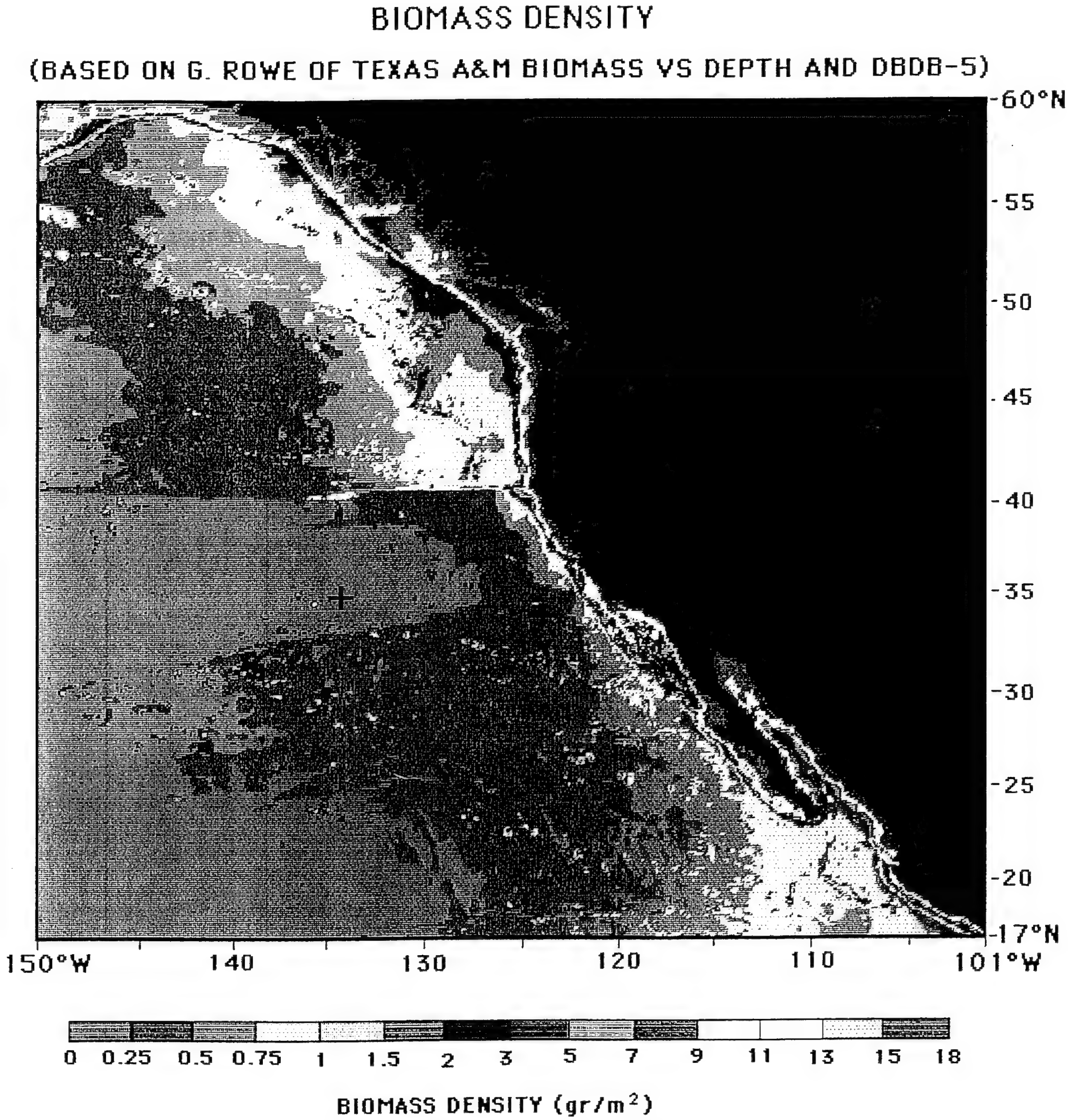


Figure 5.2.1-17. Living macrobenthos biomass density, grams organic carbon (g/m^2), for eastern North Pacific. Based on DBDB-5 depths and global biomass-depth relation provided by G. Rowe (see section 2.4.3).

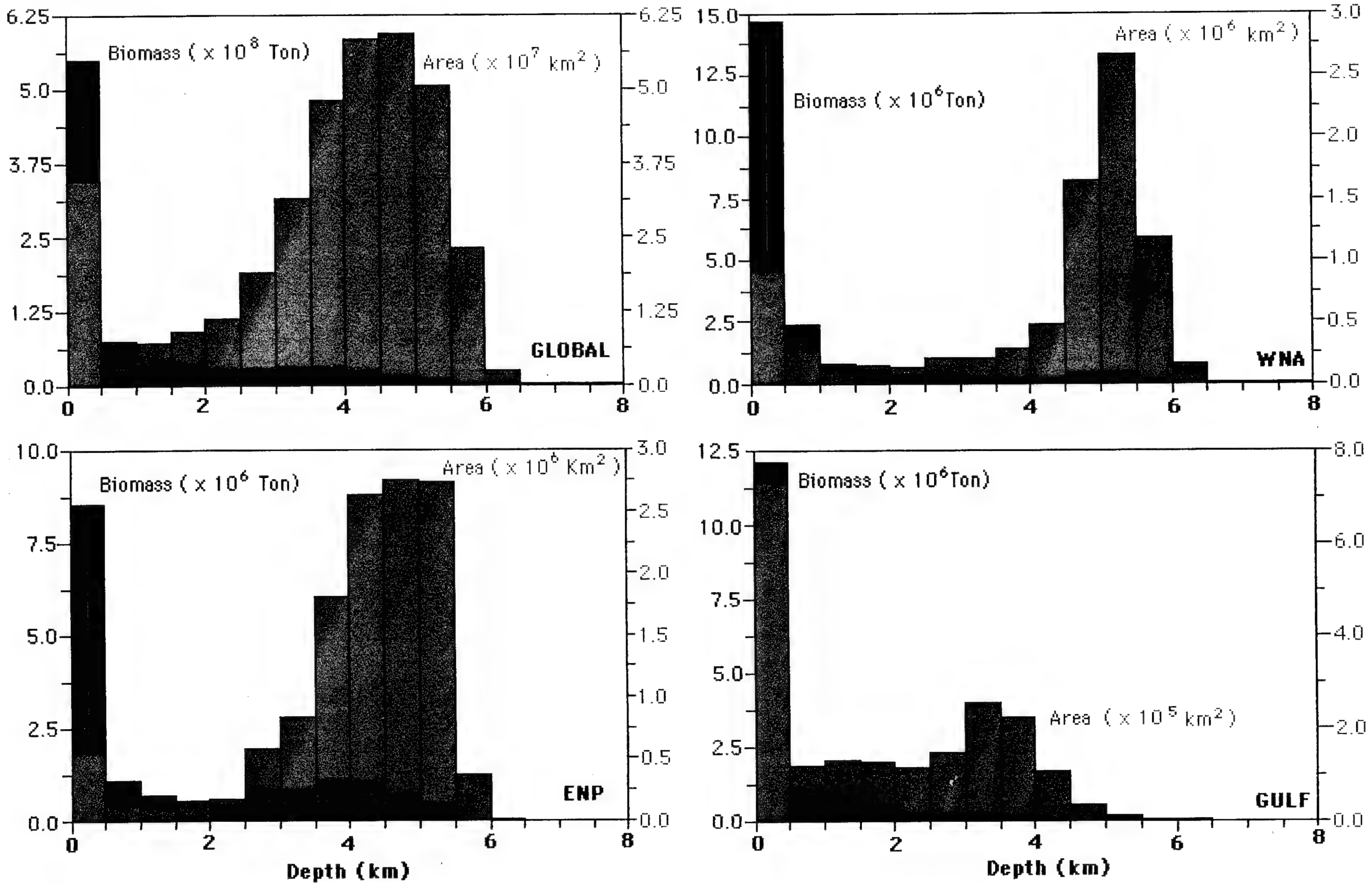


Figure 5.2.1-18. Macrobenthos biomass and ocean area versus water depth for the world oceans and for the ocean areas adjacent to the contiguous U.S. showing relatively low proportion of biomass in the abyssal ocean.

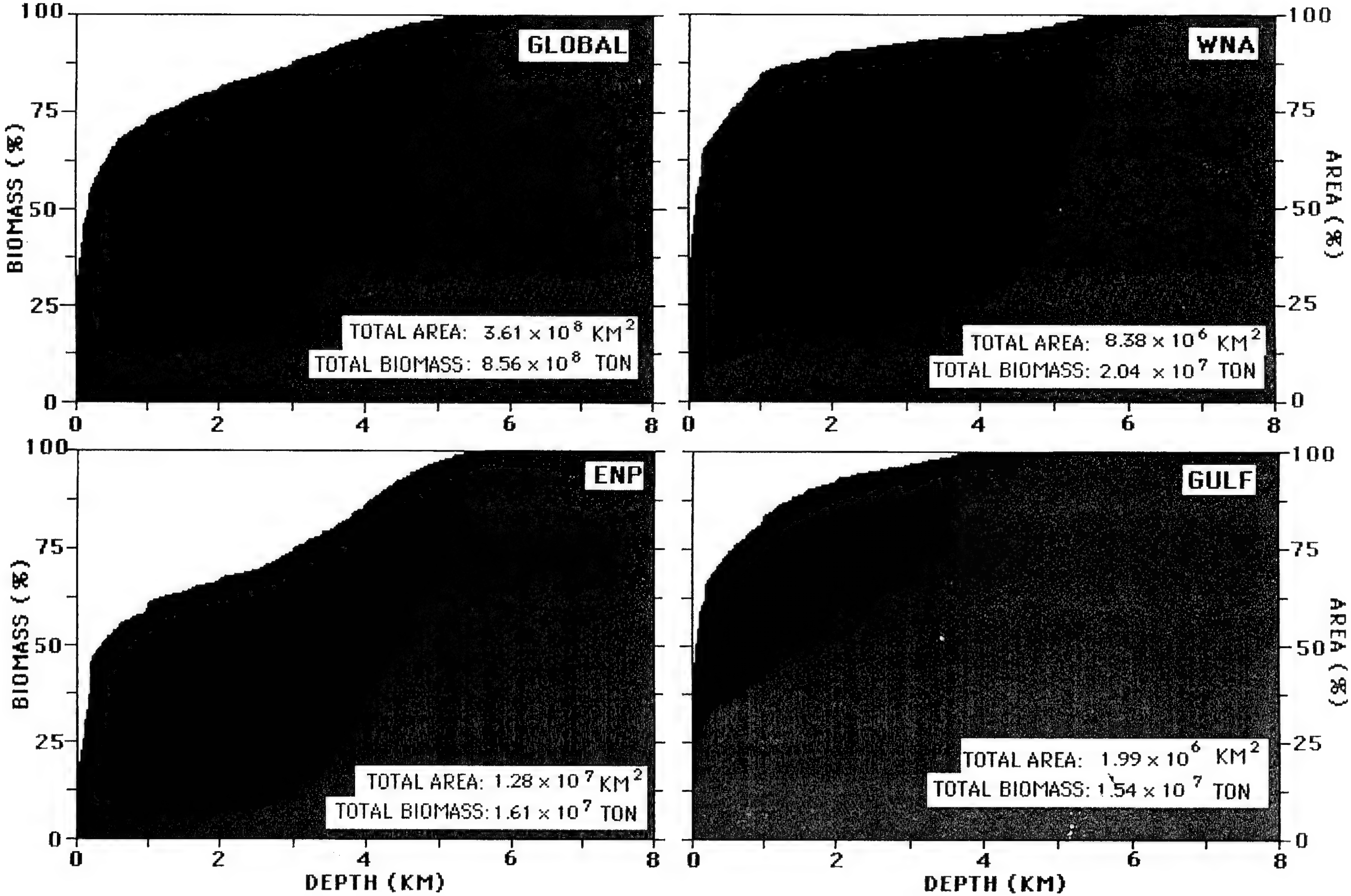


Figure 5.2.1-19. Cumulative frequency distribution of macrobenthos biomass and ocean area versus water depth for the world's oceans and for the ocean areas adjacent to the contiguous U.S.

reasons not well understood (Rowe 1994), the Gulf of Mexico as a whole is impoverished, in terms of benthic biomass, compared to the world ocean.

The biomass-water depth relation can be integrated to yield total benthic biomass for any area for the global ocean, or for given depth intervals (Fig. 5.2.1-18). The data (biomass and ocean area for each depth interval) can also be displayed as cumulative frequency distributions (Fig. 5.2.1-19). Figures 5.2.1-18 and 5.2.1-19 show that although abyssal seafloor (3- to 6-km depth) occupies a large part of the planetary surface, the benthic biomass is so low in the abyss that the summed abyssal biomass remains small compared to that of the continental shelves (Fig. 5.2.1-19). When combined with DBDB5 bathymetry, Rowe's relationship implies that two-thirds of the total benthic biomass (about 1 gigaton) lives in that 10% of the world ocean shallower than 500 m.

The relevance of the biomass-bathymetry relation for waste relocation is that it provides a quantitative (if empirical) basis for predicting the amount (by weight) of extant living matter, exclusive of bacteria, that will (or may) be affected by an abyssal waste isolation program. For example, if a Pacific waste isolation site in 4250 m water is to cover an area of 10 km^2, about 1100 kg of organisms would be affected. Similar predictions could be made for the number of species affected if quantitative relationships between water depth and biodiversity could be established, at least for specific areas and intermediate to deep water depths.

5.2.2 SEDIMENTARY REGIMES *by Frederick A. Bowles*

5.2.2.1 Introduction

From a geological point of view, the concept of placing waste on the seafloor with the intention that it remain essentially in place (contained) and isolated from the activities of mankind requires a knowledge of what environmental factors may be active on the seafloor that would negate isolation and containment. The most serious constraints placed on this scenario result from sedimentary regimes that involve gravity-driven, mass transport processes: namely, submarine slumps and slides, debris flows, and turbidity currents. Although these mechanisms are all associated with slope failure, they are also all responsible for rapidly transporting massive quantities of sediment to deep-ocean basins.

5.2.2.2 Mass Transport Mechanisms

(1) **Slumps**: Submarine slumps are coherent slope failures where a massive "block" of sediment fails or shears along a curved surface (concave upward). The downslope motion is rotary such that as the back of the block slides down, the front tips upward. This backward tilting may be so extreme that the top surface of the slump block exhibits a reverse slope and faces uphill. The actual mass translation is relatively small and internal deformation of the block is usually minimal (Jacobi and Mrozowski 1979).

(2) **Slides**: Submarine slides are differentiated from slumps in that the failed sediment mass is transported downslope along a glide plane, i.e., there is no rotation. Substantial translation occurs and the slide material is usually deformed internally (Jacobi and Mrozowski 1979); hence, slides represent incoherent slope failures.

(3) **Debris Flows**: These are essentially equivalent to mudflows on land. In the marine environment they can occur by liquefaction of the sediment (see following section on slope failure) or they may occur when a portion of the sediment in a submarine slide mixes with water and flows, rather than slides, downslope. The water is entrained as the sediment is jostled and restructured during downslope movement, increasing its fluidity and decreasing its strength. The flow can detach from the primary slide and may travel several hundreds of kilometers, covering areas of several thousands of square kilometers (Embley 1980). Deposits resulting from debris flows are rapidly emplaced. They are typically wedge-shaped, hummocky on their upper surfaces, and usually internally structureless (i.e., acoustically transparent). Texturally, they are poorly sorted, consisting of material ranging in size from fine to coarse.

(4) **Turbidity Currents**: Turbidity currents are bottom-flowing, density currents consisting of mixtures of sediment and water. Like debris flows, they are also episodic, powerful, and gravity-driven, but are capable of moving downslopes at greater speeds. In fact, debris flows are thought to represent an intermediate step between a slide and a turbidity current (Hampton 1972). The transition from debris flow to turbidity current requires extensive dilution, reducing the density of the debris flow from about 2.0 Mg/m^3 to about 1.1 Mg/m^3. Turbidity currents are a major mechanism for transporting terrigenous sediments from shallow water to the deep-ocean basins where they are responsible for constructing deep-sea fans and abyssal plains at the base of the continental margins. This transport is usually accomplished via large submarine canyons or canyon systems (Fig. 5.2.2-1) that incise the margins. Upon reaching the deep basin floor, the change in slope gradient causes deceleration of the flow and diminished turbulence causing the coarsest materials to settle out. This reduces the density of the current, causing further deceleration, and the next coarsest fraction to settle out. In this manner, a turbidity current gradually and selectively loses its sediment load as it flows across the seafloor, depositing a distinctive layer of sediment called a turbidite. Turbidites are both horizontally and vertically graded, i.e., their texture becomes finer away from the source area and the coarse material at the bottom of the layer grades to fine at the top. A single layer, representing one depositional event, can extend over hundreds, even thousands, of square kilometers.

5.2.2.3 Sediment Slope Failure

Mass-gravity transport of sediment can be explained in terms of the mechanics of slope failure and the geological conditions that trigger failure (Moore 1961). Sediments deposited on slopes will fail, en masse, when there is an increase in shear stress (beyond some critical point) or, conversely, from a decrease in shear strength.

As sediments accumulate on a slope, stresses build up from the weight of the sediment. Part of this stress (shear stress) is directed downslope. Eventually, sediment thickness can

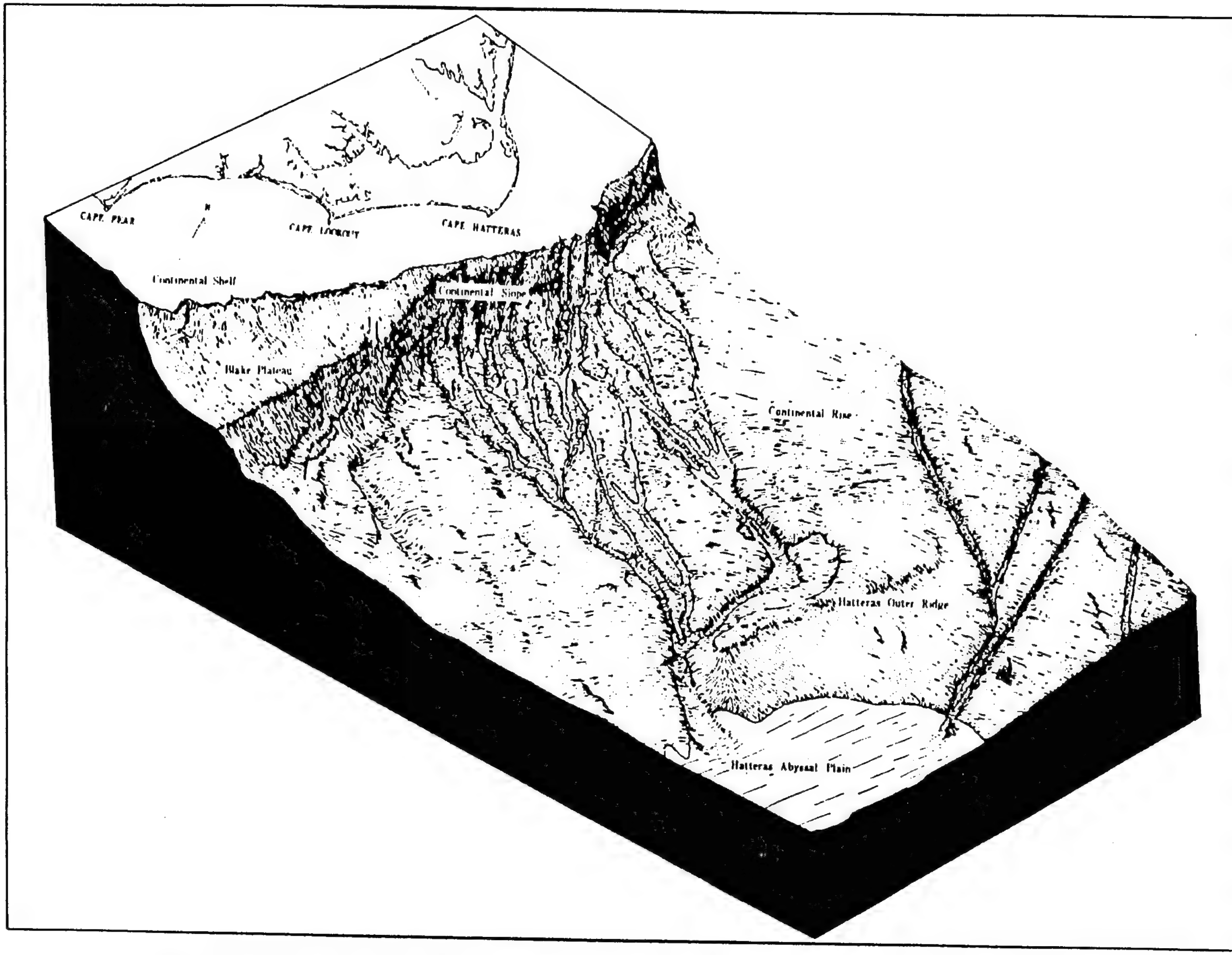


Fig. 5.2.2-1. Perspective illustration of the deep-sea canyon system off Cape Hatteras, eastern continental United States (from Emery and Uchupi, 1972).

increase enough that the shear stress exerted by the force of gravity exceeds the ability of the sediment to resist shear (shear strength), and the sediment slumps or slides. Sediment slope failure is common in areas of rapid sediment accumulation (e.g., off the mouths of large rivers) where the process of consolidation (and accompanying increase in shear strength) by expulsion of pore water cannot keep pace. Sediments of this nature are underconsolidated and can fail spontaneously, or due to physical disturbance (impact), shock (earthquakes), and transient increases in pore pressure due to the passage of storm waves.

Sediment liquefaction may also lead to slope failure. According to Moore (1962), under certain natural conditions (not fully understood) sediment grains can be deposited in a loosely packed arrangement (fabric) that renders them metastable. Physical disturbance, etc., can cause the fabric to collapse. At the instant of collapse, grain contacts momentarily break, pore pressures increase, shear strength approaches zero, and the sediment liquifies.

The slow, even deposition that takes place on most oceanic slopes today, including continental slopes, usually results in stable deposits, as opposed to metastable deposits (Moore 1962). Moreover, a substantial thickness and weight of "stable" sediment must accumulate before spontaneous failure can occur. And finally, the geological conditions that may trigger failure (e.g., earthquakes) tend to be episodic. In view of these considerations, sediment slope failure is probably rare and localized on most slopes at the present time.

On the other hand, canyons, gullies, etc., cut into the continental slopes and shelves are natural sediment traps where accelerated sedimentation can take place. These depressions, therefore, are more likely to accumulate unstable, or at least less stable deposits. Thus, if mass sediment transport occurs under present-day shelf/slope depositional conditions, it will most commonly be associated with these features.

5.2.2.4 Waste Emplacement

From the above discussion, it is apparent that locating waste disposal sites on slopes could have potentially serious consequences under a scenario of containment, if not isolation. Even on supposedly stable slopes and certainly metastable slopes, the emplacement of waste material could result in overloading the slope sediments, either suddenly or gradually, causing slope failure. Slumping or sliding is almost certain to take place, transporting both waste material and sediment downslope. During translation, a highly fluid waste (70–80% water is common) mixing with the sediment could easily transition into a debris flow or turbidity current. Indeed, if the waste is carried downslope into a contour-current regime (e.g., the east coast continental rise of the U.S.), further redistribution of the waste material by the current could be enormous. Even in the likely event that waste is placed on the bottom in bags (for containment), one could expect the bagged waste to move when the underlying sediments shear due to loading, and in all likelihood the bags would break, releasing their contents.

The most sensible scenario would have bagged waste material placed on level surfaces, such as abyssal plains. Even so, one must still contend with mass sediment movements. Waste sites located near the base of continental slopes would be susceptible to all of the

above mentioned mechanisms with the prospect of the waste-filled bags being either buried beneath a pile of sediment, or displaced by the tremendous momentum of a rapidly moving mass of sediment, or perhaps both. From a containment and isolation point of view, burial of the waste-filled bags beneath a slump or slide may indeed be desirable. On the other hand, these mechanisms could transport the bagged waste a short distance (relatively speaking), but with the likely prospect of the bags rupturing in the process. Even in this case, the released waste material would probably not get substantially redistributed as long as the normal bottom environment was tranquil (i.e., no vigorous bottom currents).

Large turbidity currents, and especially debris flows, could also bury waste material, but they would more likely redistribute waste material away from the disposal area, particularly uncontained (i.e., unbagged) waste. The maximum transporting strength of large turbidity currents would be experienced at the base of slopes where these flows first reach the flat seafloor and their momentum is still great. Thus, it is desirable in the case of debris flows to locate waste sites far out on abyssal plains beyond the frequent reach of the currents or at least where their energy is largely spent and they are more likely to deposit material rather than erode.

Turbidity currents, being the chief agent responsible for the formation of abyssal plains, may occur anywhere on an abyssal plain. They are commonly associated with submarine canyons that cut into the continental margins and tend to travel within well-defined channels on those abyssal plain areas closest to the canyons. Thus, it would be advisable to locate waste sites not only away from continental slopes but away from such channels as well. The broad areal extent of individual turbidite layers indicate that, on the median to distal portions of abyssal plains, turbidity currents tend to be broad-fronted, moving as sheet-flow between channels rather than within specific channels. Thus, it seems unlikely that turbidity currents would have much effect on waste piles located far out on the plains. Indeed, abyssal plains are depositional environments and it is likely that turbidity currents would tend to bury rather than erode and redistribute the waste.

5.2.2.5 Present-Day Perspective

The surfaces of virtually all the abyssal plains are presently covered by a veneer of fine-grained, pelagic sediment ranging up to several tens of centimeters in thickness. The exceptions to this pelagic veneer may be those areas that are very close to submarine canyons leading to major rivers. Still, the presence of this veneer attests to the fact that turbidity current events have been virtually nonexistent on the seafloor since about 11,000 years ago when sea levels approached their present levels. Prior to this time, the Earth was experiencing an ice age which, at its peak (18,000 years ago), caused sea levels to be about 100 m (300 ft) lower than today. The lowered sea levels exposed large portions of the continental shelves and caused continental erosion to increase. Thus, massive quantities of eroded continental material were transported by rivers across the once submerged shelf areas to the outer shelf/upper slope areas of the continental margins. The increased sediment accumulation resulted in a dramatic increase in mass-gravity transport for the reasons discussed above. It is thought that within a given basin, such as the western Atlantic basin, a turbidity current probably occurred every few years during glacial periods and that

perhaps one event occurred every 1000 years during interglacial periods, such as the present (Kennett 1982).

It is unlikely, then, that waste material placed anywhere on abyssal plains will be adversely effected by the sedimentary regimes that characterize these features. Nevertheless, the possibility of an isolated event always exists as evidenced by the 1929 Grand Banks earthquake that triggered a massive slide and turbidity current. The current traveled down the continental slope and far out onto the Sohm Abyssal Plain, depositing sediment over 100,000 km^2 (Heezen and Ewing 1952). If possible, then it is best to locate waste disposal sites on the distal areas of abyssal plains.

5.2.2.6 Sedimentary Regimes at Surrogate Waste Isolation Sites

(1) **Atlantic-1 Site**: The location of Atlantic-1 (Fig. 5.2.2-2) on the southern, distal Hatteras Abyssal Plain makes turbidity currents the only type of mass transport likely to reach the site of all the gravity-driven events discussed. The plain lies at the base of the continental rise off the east coast of the U.S. It is about 1000 km long, 150–300 km wide, and slopes toward the south. West of Atlantic-1, the plain is bounded by the Blake-Bahama Outer Ridge, an elongate pile of sediment that has been deposited by deep-flowing contour currents. The presence of the ridge prevents eroded continental material from moving directly offshore and onto the Hatteras plain. Neither does the Bermuda Rise, on the east side of the plain, provide a source of material. Rather, the major sediment source for the Hatteras Abyssal Plain is the continental area stretching roughly from South Carolina to New York/ New Jersey. Hudson and Hatteras Canyons, among others, are principal conduits by which turbidity currents transport coarse sediments off the shelf and onto the abyssal plain (Pilkey and Cleary 1986). The canyons, especially Hudson, are located several hundred kilometers north of Atlantic-1. Consequently, only the largest of turbidity currents are likely capable of reaching the site, and evidence indicates that such currents are unlikely to happen under present day interglacial (i.e., high sea level) conditions. Major, worldwide, sea-level fluctuations are related to the advance or retreat of the polar ice caps and occur on timescales of thousands of years. Consequently, present-day sea levels are not expected to change significantly (up or down) for many years to come.

(2) **Atlantic-2 Site**: This site is located just to the east of the Bermuda Rise in the axial depression of a fracture zone that terminates against the rise (Fig. 5.2.2-2). The remoteness of the site from continental areas and its location in a depression offers certain advantages. First, the site is not subject to the enormous, gravity-driven mass transport events that can develop on the continental margins. Nevertheless, the high-standing fracture zone topography around the depression might generate local, small-scale (i.e., low-mass) slumps and slides that could, in turn, generate small-scale debris flows and turbidity currents. Secondly, no matter which mass transport event occurs, it would be contained within the confines of the depression. The impoundment of sediments within small, enclosed basins (sediment ponding) is commonly recognized in seismic profiles of the seafloor (Hersey 1965). Small, enclosed basins, then, are desirable locations for waste disposal since the waste, like the sediments which find their way into the basin, would remain impounded. The fact that the turbidity currents, for example, would probably redistribute the waste throughout the basin is not

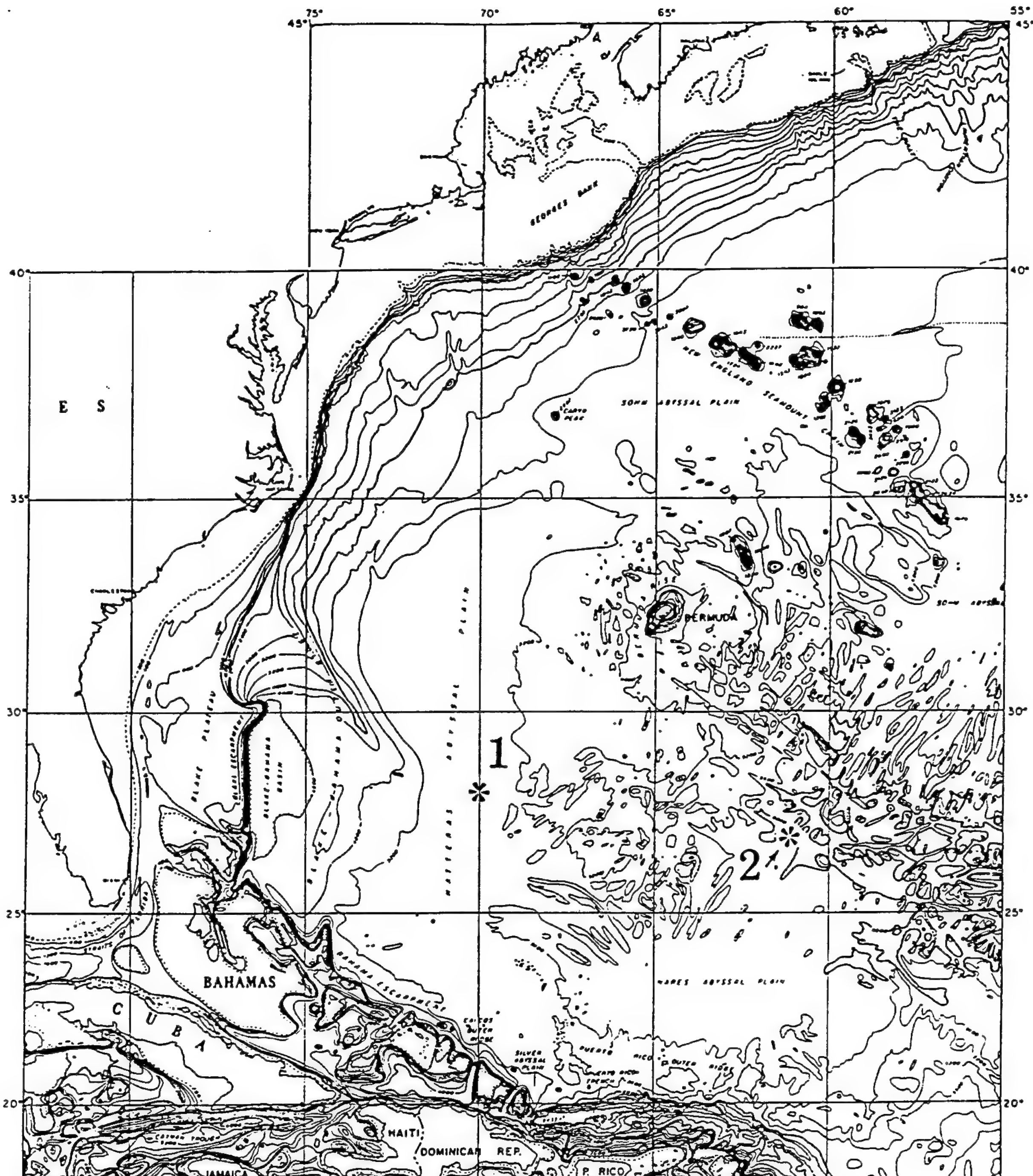


Fig. 5.2.2-2. Bathymetric-physiographic map of the western North Atlantic. Asterisks denote locations of surrogate waste isolation sites. Contours in meters.

viewed as a problem because the waste would still remain in the basin. Moreover, sediment ponds are, by definition depositional, environments and the tendency would be to eventually bury the waste. It should be pointed out that the fracture zone marks the extreme (distal) northern boundary of the Nares Abyssal Plain, a remote feature that is connected to the Hatteras Abyssal Plain by Vema Gap. At one time, turbidity currents originating on the margins of North America transported material across the Hatteras Abyssal Plain, through the Vema Gap, and onto the Nares Abyssal Plain. Presumably, only the largest and most powerful turbidity currents would be capable of reaching Atlantic-2 today. As discussed, the probability of a single turbidity current event, let alone such a large one, is low, given present sea levels. Even so, a "rogue" turbidity current reaching Atlantic-2 would probably lack sufficient energy to do much more than deposit fine-grained sediment around the waste material.

(3) **Pacific-1 and -2 Sites**: Both of the Pacific surrogate sites are located in an abyssal hill province (Fig. 5.2.2-3). Most abyssal hills are elongate, having an elliptical shape, and can range in height from 50–1000 m with slopes of 1–15°. Large, but representative, hills off California are 30–40 km long, 8–10 km wide, and 200–300 m high (Menard 1964). The hills take their shape from the underlying basement surface. In the Pacific, the relief of this original surface is buried and smoothed by less than 100 m of fine-grained sediment. The combination of thin cover and extremely slow sedimentation rate (less than 1 mm/1000 yrs) have resulted in stable sediment deposits that are not likely to fail. Indeed, slumps and slides do not appear to be common occurrences in abyssal hill provinces. As a result, gravity-driven mass sediment transport is probably not a major obstacle to waste disposal at these sites, especially if the waste is placed in the low areas between hills which constitute optimal waste disposal locations as discussed for Atlantic-2. It is important to note that the abyssal hills of Pacific-1 are located just beyond the edge of the Monterey Fan which is constructed by turbidity currents. If, or when, the fan will encroach upon and engulf these hills is difficult to say; however, fan turbidity currents do not presently affect Pacific-1.

(4) **Gulf of Mexico Site**: Because of the exclusion definitions that initially constrain all the site locations, only two small areas of the Gulf of Mexico remain as possible waste disposal sites. The one chosen (Fig. 5.2.2-4) is located on the Sigsbee Abyssal Plain just south of the rise at the base of the Sigsbee Escarpment. Despite the fact that Alaminos and Keathley Canyons are situated due north of the site, this location was opted because (1) both canyons are presently inactive and (2) the predominant direction of mass sediment transport on the Mississippi Fan is toward the east/southeast toward the other potential site location. The observation that the Sigsbee Abyssal Plain is covered with a thin layer of fine-grained sediment bespeaks the absence of turbidity currents.

5.3 Chemistry

5.3.1 Interaction Between Dissolved and Particulate Matter in Seawater

by Robert E. Pellenbarg

There are two large classes of matter which occur in the oceans. These classes are inorganic and organic and will be discussed separately. Of major concern for both classes

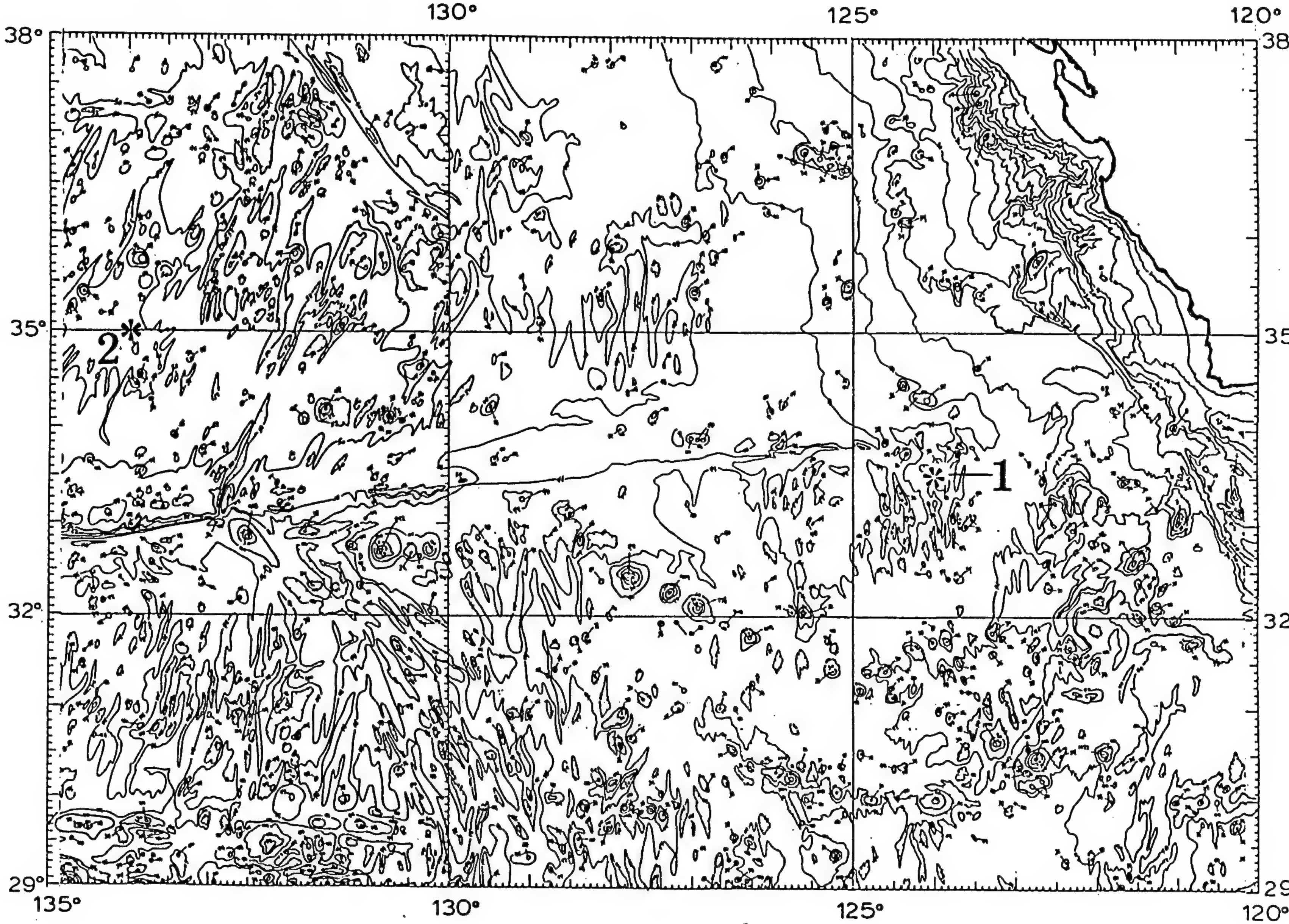


Fig. 5.2.2-3. Naval Oceanographic Office World Relief Map, NP-9, of the eastern North Pacific off southern California. Asterisks denote locations of surrogate waste isolation sites. Contours in meters.

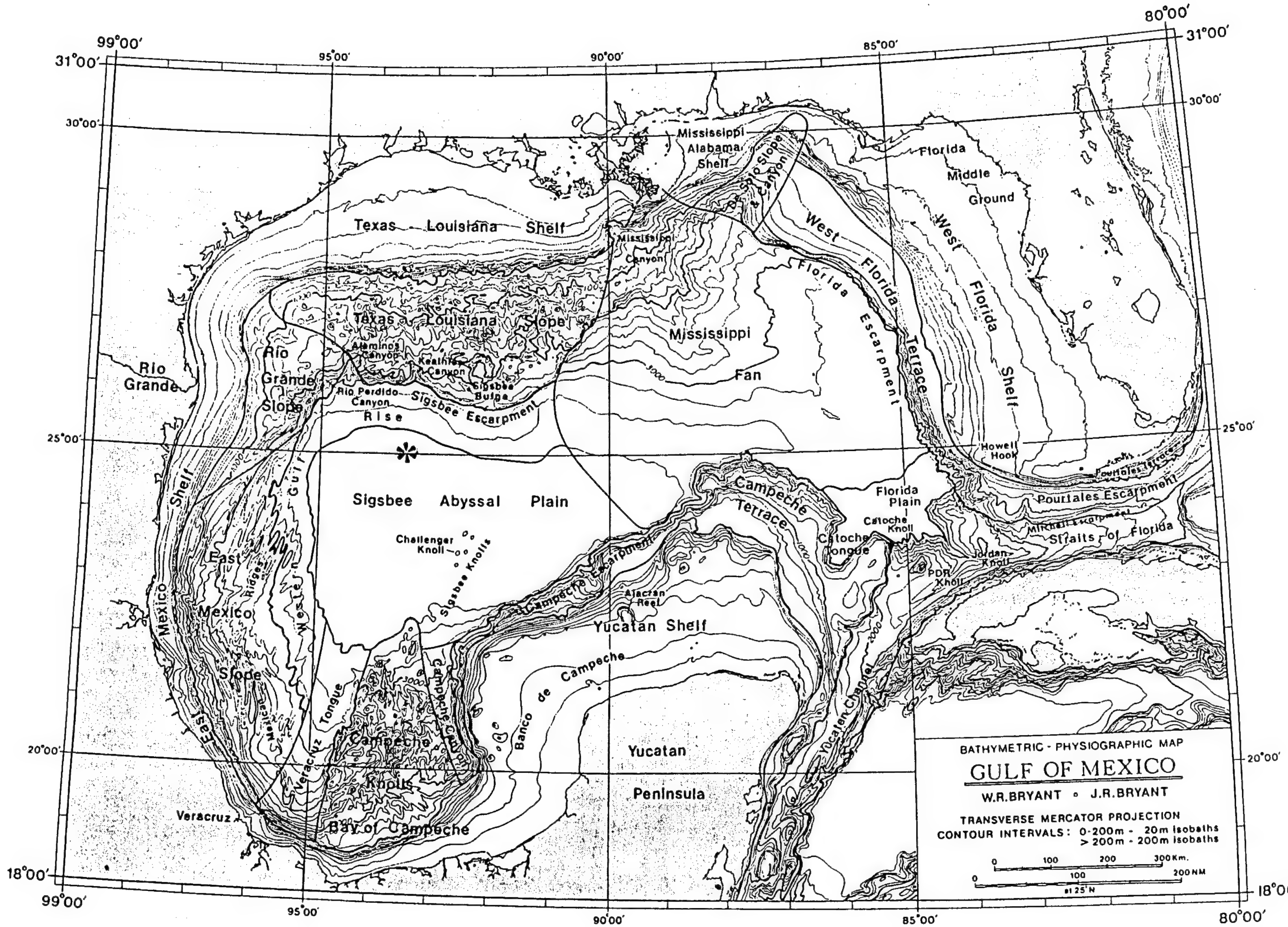


Fig. 5.2.2-4. Bathymetric-physiographic map of the Gulf of Mexico. Asterisk denotes location of surrogate waste isolation site (from Bryant et al, 1991).

in the context of the ASWI project is what can be expected to occur to dissolved inorganic and organic matter released to the ocean. Specifically, there is a need to understand diagenetic processes affecting dissolved matter in the ocean so that one can identify the initial fate of dissolved matter released from wastes emplaced on the abyssal plain. There is essentially no information in the literature specifically dealing with the diagenesis of dissolved species in the deep sea. However, there is much knowledge addressing the fate of dissolved material in estuaries where the fresh water from continental runoff mixes with the high-ionic strength seawater. Some of what is known about the estuarine chemistry of dissolved matter may be applicable to what can be expected to happen to such material in the deep sea.

Three broad categories of processes can affect dissolved and particulate materials in the estuary, and by analogy, the deep sea. First, dissolved matter can precipitate to yield new solid phases, or small particulates can aggregate to give larger particles. Second, dissolved material (especially organic matter) can sorb onto solid phases (especially clay particles) already present in the system. And third, products from the first two processes, or from particulates not changed chemically or physically by admixture with sea water in the estuary, can release dissolved species via one or more well characterized processes.

The situation involving dissolved iron in natural waters is a good example of dissolved matter yielding a new phase upon admixture with seawater. Coonley et al. (1971) describe in detail an estuarine situation in which mildly acidic fresh water carries unusually high loadings of dissolved iron into an estuary. As the acidic water mixes with the basic (pH ~ 8) seawater, the acidity of the fresh water is neutralized, and the dissolved iron rapidly flocculates out of solution as hydrous oxide particles. Further, there is strong evidence that in cases where there is insufficient dissolved iron to allow for the formation of iron-rich flocs, the hydrous iron oxides can coat solids, such as clay particles, as fresh water and seawater mix in the estuary (Aston and Chester 1973; Gibbs 1973). Iron hydroxide, as flocs or coatings, is widely recognized as an excellent ion exchange material. Indeed, iron hydroxide is used as an analytical reagent for the collection of dissolved trace metals and radionuclides in seawater (Wong et al. 1970), and, once formed, iron hydroxide could be expected to sorb dissolved trace metals.

Even as processes in the estuary act to precipitate certain dissolved inorganic species such as iron, parallel processes act to remove dissolved organic matter. The removal of dissolved organic matter during estuarine mixing is a well established phenomenon (Sieburth and Jensen 1968; Matson 1968; Swanson et al. 1972; Gardner and Menzel 1974). Coagulation of the dissolved organic matter seems to be the major process, with the coagulation abetted by the high ionic strength of the seawater. Specifically, for large organic molecules dissolved in fresh water (e.g., ionized hydroxide groups along macromolecular chains will tend to keep such high molecular weight species in solution in fresh water) and suspended clay particles, contact with seawater causes the charged sites on the molecular chains or clay particles to be neutralized (especially by sodium, potassium, or magnesium ions), so that the resulting neutrally charged particles can agglomerate and settle out of the water column. Many organics can end up as coatings on particles in the estuarine mixing regime (Swanson et al. 1972; Burton and Liss 1976). Swanson et al. (1972) estimate that 25% of the humic matter present in a Gulf of Mexico salt marsh is due to flocculation of the

dissolved organic matter carried into the marsh by tidal flow. These documented examples argue strongly that any dissolved organic matter that may leach from waste emplaced on the abyssal plain would readily flocculate by analogous processes.

The ionic nature of seawater can serve both to cause flocculation of organic matter and to release substances previously immobilized. This latter process mostly affects inorganic species and must be considered on an element-by-element basis. For example, sodium ions can displace calcium ions sorbed to montmorillonite in fresh water regimes, as brackish to seawater regimes are encountered. There is evidence that phosphorus can be desorbed from suspended particles in estuarine regimes (Upchurch et al. 1974), while Kharkar et al. (1968) suggest that cobalt can be similarly desorbed from particulates upon contact with seawater. Kharkar's work shows that for other trace metals, such as chromium and molybdenum, desorption processes yield few dissolved ions of these elements. Laboratory studies have shown that calcium and magnesium ions are not consistently effective at displacing sorbed trace metals from particulate surfaces (Johnson et al. 1967; Gibbs 1973; Forstner and Wittman 1983).

Additional laboratory research has examined the partitioning of inorganic and organic species between phases in various systems. For example, McKee et al. (1989) describe the partitioning of lead, zinc, copper, iron, and manganese across the sediment-water interface in fresh water lakes; they report that many natural processes can mobilize the metals in sediments as a function of season, local redox conditions, and biological activity (especially through bioturbation, i.e., sediment reworking by benthic animals). Rygelski et al. (1984) examine abiotic metals partitioning in another fresh water system, Saginaw Bay (Lake Huron), while Oliver (1987) addresses organics partitioning in the St. Clair, Detroit, and Niagara Rivers (all fresh water). Jeng et al. (1992) provide data on soil sorption coefficients, but the applicability of these data to processes on the abyssal seafloor is uncertain. Strobel et al. (1981), who studied the fate and sediment-water partitioning of Kepone (a pesticide) in the riverine and estuarine portions of the James River in Virginia, found that most Kepone resides in the sediment, especially in the more saline portions. Gschwend and Wu (1985) found that the constancy of sediment-water partition coefficients of hydrophobic organic pollutants varied little over rapid salinity changes. Polychlorinated biphenyls (PCBs) were the focus of many studies, such as those of Horzempa and DiTora (1983) and Baker et al. (1986), both of which show that the hydrophobic PCBs will reside in the sediments of aqueous systems.

The above discussion focuses almost exclusively on abiotic processes that occur in the estuarine regime. The processes are offered as analogs for what could be expected to happen to dissolved substances leaching out from emplaced wastes on the abyssal seafloor. Biological processes significant in most estuaries by analogy can be expected to be important on the abyssal seafloor. Biological processes are important mobilizers of matter, both inorganic and organic, in all terrestrial, estuarine, and oceanic systems. Components of matter can be mobilized, released, or retained by biota, passed into successive trophic levels of the food web, and eventually returned to the cycle as inorganic components of the ecosystem.

The concept of octanol-water partition coefficients has been used for years to assess the degree to which a particular substance may partition between biota (modeled by octanol) or the abiotic components of the biota's environment (modeled by the water). Sabljic et al. (1993), Sicbaldi and Del Re (1993), and Patil (1994) report on research allowing one to measure octanol-water partition coefficients from a process which involves shaking the compound in question with a mixture of octanol and water in a separatory funnel, then assaying the separated phases. Larsen et al. (1992) and Sotomatsu et al. (1993), using this and other techniques, report measured and calculated partition coefficients for PCBs and ortho-substituted aromatic substances. While octanol-water partition coefficients for certain materials exist, they are not generally available in the literature; the coefficients for many specific materials still need to be measured or calculated. Various researchers have investigated the relationship between the hypothetical model (octanol-water as mimicking biota-environment) and the reality of the environment. Just et al. (1990) followed the partitioning of Lindane among sediments, water, and shrimp, while Binstein et al. (1993) did similar work involving fish and Scheunert et al. (1994) focused on land plants. Saito et al. (1993) related toxicity to goldfish cells to the octanol-water coefficients of a variety of chemicals. There is sparse and scattered literature which provides guidance as to how certain classes of organic compounds may interact with biological systems; however, specific data applicable to the abyssal seafloor is lacking, and must be addressed in further research.

Research described above has made good use of the octanol/water partitioning coefficient concept as a predictor of the fate of organics. Yet, the investigations do not, by design, address potential ultimate fate of the target compounds. By ultimate fate, one means defining the final degradative paths for selected materials. For example, Hill (1967) examines the degradation of selected chlorinated pesticides in model and laboratory studies, while Menzie (1972) follows their fate in the open environment. Kilgore et al. (1972) catalog extensive research on degradation paths for synthetic organic materials, while Matsumura (1982) focuses on both microbial and photolytic degradation paths for pesticide degradation. Coats (1992) examines pesticide degradation mechanisms. Klopffer (1992) emphasizes pesticide degradation by photochemical processes, but such processes would be inoperative in the abyssal ocean environment. There is little known about microbial processes in the abyssal ocean, so one can only speculate on the comparability to the abyssal environment of microbial degradation processes examined by these authors. Available evidence suggests that a majority of organic matter associated with wastes emplaced on the abyssal seafloor would tend to stay with the waste, especially as coatings on the particles constituting the waste mass, and would be slow to degrade (particularly such refractory compounds as chlorinated pesticides).

From a monitoring standpoint it is useful to consider how one could select a substance for use as a chemical tracer for movement of the waste materials. The tracer could be a compound added to the waste before emplacement, or could be a naturally occurring component of the waste. Any tracer selected for monitoring purposes must be inert to both biological and abiotic processes, and be easily assayed in samples collected near the emplaced waste. In the former case, sulfur hexafluoride is a very good candidate. Sulfur hexafluoride has been used as a tracer for the movement of oceanic water masses (Wanninkhof et al. 1991; Watson et al. 1991; Ledwell and Watson 1991) with marked success. For the abyssal

seafloor case, soluble or corrodible (e.g., magnesium) containers of liquid sulfur hexafluoride could be added to the emplaced waste, and water flowing over the waste could be optically monitored in situ for the sulfur hexafluoride tracer. Alternatively, one could choose to seek a specific chemical tracer in the emplaced wastes on a batch-by-batch basis, or select a generic chemical tracer present in all batches of waste. Silicone is an excellent candidate for use as a generic tracer, as silicone is present in all municipal wastes as a byproduct of the use of consumer products (e. g. cosmetics, cooking oils, paper) containing silicone (Pellenbarg 1979a, 1979b, 1982, 1984; Pellenbarg and Tevault, 1986). In either case, the reality of the situation argues that any slightly soluble candidate tracer (e.g., sulfur hexafluoride or silicone) would tend to reside on particles in the emplaced mass, as will higher molecular weight organic matter in general.

5.3.2 Geochemical Diagenesis of Emplaced Wastes *by Robert E. Pellenbarg*

A major factor affecting any decision to place wastes on the abyssal seafloor is an understanding of what physical or chemical processes may act to release the emplaced wastes or components thereof. Physical impacts on the wastes will be addressed in detail elsewhere (see Section 5.1, **Physical Oceanography**). For the current discussion, bottom currents sweeping the waste isolation region are a consideration because these can influence the chemical diagenesis of the emplaced wastes by providing oxygen to the wastes. Indeed, in the abyssal seafloor regions, the bottom waters are uniformly well oxygenated (Broecker 1974).

However, while the surface of the wastes may be influenced by well-oxygenated water, the interior mass of the wastes will exhibit a markedly different oxygen regime. Biologically-mediated diagenetic processes within the mass will consume the available oxygen and render the interior of the mass anoxic. Once the waste mass has been depleted of oxygen, predictable chemical processes will begin (see Section 5.3.4, **Predictions of Near- and Far-Field Effects Resulting from Introduction of Wastes to Abyssal Environments**); these processes can mobilize various components of the wastes.

There is sparse literature addressing specific diagenetic processes affecting sediments of the deep sea. In contrast, there is a wealth of information describing the biologically-mediated diagenetic processes in other oceanic regimes. For example, numerous researchers have worked to understand biological and chemical processes affecting sediments in the salt marsh. For purposes of this study, the relatively well-understood geochemical processes of the salt marsh will be described; then, analogies will be made to the abyssal ocean. The appropriateness of these analogies is currently unknown and would have to be justified by measurements.

The salt marsh is a unique ecosystem occupying vast areas of the east and Gulf Coasts of the United States, and other areas of the temperate latitudes. The salt marsh is characterized by extensive stands of the grass *Spartina alterniflora*, fine-grained sediments with low porosity, and diurnal flooding with saline water (Hanson and Snyder 1980; Lion and Leckie 1982). Salt marshes occupy low-energy regimes, typically bay margins. The growth of *Spartina* produces organic carbon (e.g., plant debris) which is transported into the surrounding surface waters and into sediments supporting the marsh plants.

Changes occur in salt marsh sediments on a seasonal basis. In the summer and early fall (local warm seasons), *Spartina* releases organic matter to the marsh sediments. Bacteria in the sediments consume this organic matter and rapidly exhaust the oxygen in the sediments; little oxygen can diffuse into the sediments as they are of low porosity. Consumption of organic matter continues using sulfate (from the ocean-derived saline waters of the marsh) as an oxidizer. In the winter (local cold season), these processes are greatly diminished (Lord and Church 1983; Pellenbarg 1984).

These processes occurring on a seasonal basis in the salt marsh sediments can be summarized in the following equation:

$$2[(CH_2O)_c(NH_3)_n(H_3PO_4)_p] + c(SO_4^=) \text{ ----}$$

$$2c(HCO_3^-) + 2n(NH_3) + 2p\ (H_3PO_4) + c(H_2S) \qquad (1)$$

(from Richards 1965), where CH_2O represents organic matter, and c, n, and p represent carbon:nitrogen:phosphorus (c:n:p) ratio of this organic matter. Sulfate reduction process releases ions such as carbonate, ammonium, phosphate, and sulfide to sediment pore waters (water retained between sediment grains/particles). These ions, in turn, can affect the mobility of other species (e.g., metals) associated with the sediments. Deep within the fine-grained salt marsh sediments, the reaction will result in reducing conditions with a net release of sulfide, as sulfate is consumed locally. Nearer the surface of the sediments, some oxygen can diffuse into the sediments, around or through *Spartina* roots; this oxygen will serve to preserve sulfate and to consume CH_2O in aerobic biochemical processes, with CO_2 as a major byproduct. This oxygenated layer can be up to 5–8 cm thick, depending on local conditions in a specific salt marsh.

As given in equation (1) above, sulfide species (H_2S, HS^-, $S^=$) are byproducts of sulfate-mediated consumption of organic matter. These sulfide species, in turn, can affect the mobilization of a variety of other ions. For example, the process summarized in the following equation is one in which sulfide reacts with hydrous iron oxide to yield pyrite and is locally important in the salt marsh:

$$FeOOH + (3/2)HS^- + (1/16)S_8^0 + (3/2)H^+ \text{ ---- } FeS_2 + 2H_2O \qquad (2)$$

(after Lord and Church 1983). This reaction specifically shows a case in which HS^- serves as a reducing agent for a metal oxide (iron, in this instance). Other metal oxides (e.g., cobalt, manganese, chromium) could, in theory, similarly react with the reducing agent HS^- and become mobilized. Note further, however, that some metallic species (e.g., lead, cadmium, or mercury) may become immobilized via reaction with sulfide species to give very slightly soluble metallic sulfides.

The compound pyrite (iron sulfide, Eq. (2)), especially in a finely divided state, is metastable in that it will react with oxygen to yield iron oxides and sulfuric acid. This is precisely what occurs in abandoned coal mines where pyrite in the coal oxidizes on contact with air (oxygen) to give (sulfuric) acid mine runoff. Thus, we can expect pyrite to be formed deep within a sediment mass (in the salt marsh) or, by analogy, within an

emplaced waste pile on the abyssal seafloor. Further, pyrite will oxidize when, by diffusive processes, it comes in contact with overlying oxygenated water. Hydrogen ion, a powerful mobilizer of metal ions, is a key byproduct of pyrite oxidation.

The mobilization process may reflect simple dissolution of metallic oxides or carbonates. For example, nickel and zinc oxides (components of municipal incinerator ash) dissolve readily in acid, as do all metal carbonates. Further, hydrogen ion, and sodium, potassium, and magnesium ions in seawater, readily displace weakly held metallic ions sorbed onto clay particle surfaces. Thus, metals sorbed onto clay particles (from dredged material, for example) could be released by contact with hydrogen ion produced from the oxidation of pyrite in a waste pile, or by simple contact with the high ionic strength of seawater in the abyssal ocean (Kharkar et al. 1968). To summarize, the seawater of the abyssal ocean can affect emplaced wastes in at least two ways: as a source of oxygen for diffusion into the waste pile to affect oxidation-reduction reactions occurring in the mass of emplaced waste, and as a source of ions to displace weakly-held metallic species associated with the particles constituting the waste itself.

The above discussion focuses on sulfur chemistry as affected by organic matter, and how the sulfur chemistry can influence metal geochemistry in temperate salt marsh sediments. In certain geochemical situations, the biologically mediated processes mentioned previously may proceed to the point that all sulfate in the pore waters is consumed by the bacteria in sediments. In the absence of sulfate ion, an anaerobic diagenetic pathway is utilized by bacteria in which carbon dioxide is reduced to methane gas. Methane gas may accumulate in the sediment, or migrate into overlying waters. The process is summarized in

$$2(CH_2O)_n \text{ ---- } nCH_4 + nCO_2 , \tag{3}$$

where organic matter serves as both a carbon source of bacterial fermentation and as a hydrogen source to reduce carbon dioxide (Berner 1971). Again, note that Eq. (3) cannot occur in the presence of sulfate ion. However, it is entirely probable that an emplaced mass of waste on the abyssal seafloor could, in the presence of methanogenic bacteria, become a source of methane to surrounding waters. Methane, in turn, could serve as a carbon source for other microbial species colonizing the surface of the mass.

There is one final observation based on Eq. (1) which is significant to the topic of this discussion. The rate of reaction described by Eq. (1) is controlled by several factors (a) the chemical composition of the material being decomposed, (b) the rate of the decomposition reaction, (c) the diffusion of ions within the sediment or waste mass as a function of the porosity of the material in question, and (d) the rates of reactions consuming the byproducts of the decomposition processes.

It is clear from these factors that Eq. (1) provides general guidance as to what to expect once a mass of material containing organic carbon is shut off from an oxygen source. However, note that the rate of diagenetic process addressed in Eq. (1) may be exceedingly slow on the abyssal seafloor, if only from a temperature perspective. The cold temperature of the abyssal ocean will slow the process of Eq. (1) markedly. The chemical composition of the emplaced wastes will also affect the rate of diagenetic reactions. For example, most

dredged material and fly ash will be much more inert than will organic-rich sewage sludge in the abyssal seafloor environment. Dredged material from brackish or fresh water coastal sites will have a lower ionic strength pore water than does the full-strength seawater of the abyssal seafloor. In such a situation, fresh water will tend to diffuse out of the waste, and such diffusion may well serve to transport dissolved ions from the waste mass. The analogies provided herein from salt marsh and other coastal examples provide only preliminary indications of what could happen diagenetically to wastes emplaced on the abyssal seafloor; each situation requires a case-by-case evaluation as to what will occur in situ if wastes are so emplaced.

5.3.3 Potential Impacts of Wastes Emplaced on the Abyssal Seafloor

by Robert E. Pellenbarg and Robert A. Lamontagne

In recognition of the deficiency of detailed understanding of deep-sea ecosystems, it is useful to examine what is known about analogous, more accessible, marine ecosystems, and how such ecosystems assimilate wastes. Perhaps the most well-known and documented waste disposal site in marine waters is the New York Bight where millions of tons of waste per year have been deposited. What is known from this long-term natural "experiment" is helpful in understanding what could happen in the abyssal ocean.

Until recently, up to some 3×10^6 m^3 of sewage sludge were dumped per year about 25 km from the mouth of New York Harbor (see Section 1.5.5, **MESA/New York Bight Studies**). The sewage sludge is rich in organic carbon and nitrogen, yet the marine sediments in the vicinity of the dump site are fairly low (0.4–5%) in organic carbon content (Duedall et al. 1975). This observation suggests that the New York Bight has been able to assimilate much of the organic carbon in sewage sludge deposited there. This proposition was examined by Grunseich and Duedall (1978) in a controlled laboratory setting. They placed sludge, disposal site sediments (as inoculant), and seawater in small plastic chambers held at 21°C (simulating summer conditions) and 4°C (simulating winter conditions) under aerobic (oxygenated) and anaerobic (anoxic) conditions. Their results showed that the sewage sludge decomposed more rapidly under aerobic conditions than under anaerobic conditions, and that low temperature delayed the onset, but not overall rate, of sludge decomposition. On the basis of these findings, they recommended that aerobic conditions be assured in disposal operations by spreading the sludge as widely (thus as thinly) as possible at the disposal site. They found that sludge layers more than about 1 cm thick encouraged less rapid anaerobic processes affecting the assimilation of the emplaced material.

Nedwell and Lawson (1990) extended the earlier work of Grunseich and Duedall (1978) by measuring the relative rates of degradation of different components of sewage sludge, and rates of mineralization (mobilization to release) of metals from sludge. Specifically, they added sludge suspended in seawater daily to their test chambers, which were kept well-aerated, and followed carbon dioxide production as a measure of sludge mineralization (decomposition). Nedwell and Lawson (1990) report the following observations (1) added sludge was effectively mineralized as a function of loading (heavy loading tended to slow the decomposition process) in all test chambers, (2) the chambers and underlying sediments never went anoxic, (3) metals (zinc and lead) were essentially held, as sulfides, in the

sediments and (4) at no time was methane detected as a byproduct of decomposition. This last observation is consistent with other research which has shown that methane cannot form in systems containing sulfate (Nedwell 1984). Methane can and does form in the absence of sulfate (see discussion below).

The two research efforts described previously show that well-oxygenated coastal marine ecosystems can assimilate such easily digested material as sewage sludge. The sludge contains sufficient quantities of carbon, and some nutrients (especially nitrogen and phosphorous), which enable endemic microbial biota to digest the sludge material. At least some metals that form insoluble sulfides (e.g., zinc and lead) are largely immobilized as the sludge is digested. Sulfide, locally produced as the sediment column goes anoxic in response to the sludge carbon input, acts to tie up calcophile metals. Data are available concerning the average composition of municipal sewage sludge. Table 5.3.3-1 lists representative concentrations of metals that are found in pressed sludge from Wards Island in the East River in New York (Walker 1991). The pH of these sludge cakes range from 7.8 to 8.6. The pH of seawater is ~ 8.1 and, as such, there would be little if any major change in the pH balance when the sewage sludge is on the seafloor. The first column of Table 5.3.3-1 identifies the analytes, the second column is the average concentration for the total analysis from the pressed sludge, and the third column is the average concentration for the leachate analysis using the Toxic Characteristics Leaching Procedure Test method (TCLP) (Roethel et al. 1990). The TCLP uses glacial acidic acid to attain a pH of 2.8, 18-hr extraction, and end-over-end agitation before analysis. Even with this very strenuous extraction procedure, the concentration of extractable metals is very low. In the waste emplacement procedure proposed in this study (see Section 1.4.1), the material in question would not be subjected to such an extraction process. Instead the material would be exposed to a slightly basic pH, cold temperatures, and high pressure which would not increase the solubilization of the metals into seawater. Further, the effect of mobilizing metals by digestive processes of deep-sea deposit-feeders would result in only trace amounts being potentially assimilated by the fauna. We do not know the effect of trace amounts (ppm, ppb) of metals on the biota of the abyssal seafloor.

Almost all metals are undersaturated in open-ocean conditions based on solubility and equilibrium reactions (Goldberg 1975; Krauskopf 1956). Krauskopf (1956) has shown experimentally that adsorption on suspended solids is probably the major pathway for reducing the concentration of metals in seawater to undersaturation values. Several trace metals, including mercury, are strongly concentrated in the finer size fraction of sediments (Turekian 1965). The various forms of binding that can occur between metals and organic materials (clays, ligands, amino acids, etc.) are adsorption — physicochemical, electrostatic attraction, changes in hydration state of the solid or adsorbate, covalent bonding, Van de Waals, or hydrogen bonding (Parks 1975).

Most of the metals identified will sorb onto the fine particles, clays (Bourg 1981), that are present in the sludge. Sewage sludge also contains many types of natural ligands which will complex with metal ions. The presence of biofilms of certain bacteria promote the complexation and sequestering of organics and heavy metals (Walch and Weiner 1994).

Table 5.3.3-1. Metal Concentration from Sludge Using TCLP Method (from Walker 1991).

Analyte	ppm, Total Analysis	ppm, TCLP Leachate
pH	8.1	5.2
ammonia nitrogen	1880	
cyanide	0.3	
antimony		0.02
arsenic	<5	<0.05
barium	540	0.9
cadmium	5	<0.01
chromium	120	0.06
copper		0.02
hexavalent Cr		<0.01
lead	270	<0.02
mercury	3	3
molybdenum	7	0.05
nickel	47	0.34
selenium	<2	0.002
silver	30	<0.01
zinc	1100	0.60

Others will form insoluble or slightly soluble oxides; iron, manganese, cobalt, and chromium are examples. Trace metals can be held in the lattice of clay minerals or between the sheets of clay minerals of continental origin (Goldberg 1975).

Chromium would be reduced to the nontoxic trivalent state from its toxic hexavalent state (if not already in that oxidation state when emplaced). Zinc, lead, cadmium, and mercury would be present as insoluble sulfides when anaerobic conditions exist (Nedwell and Lawson 1990). Zinc is not known to concentrate upward in the food chain (Jernelov 1974). Cadmium binds strongly to organic substrates and complexes to a higher degree than mercury in seawater (Jernelov 1974). Little evidence exists for bioaccumulation of cadmium. The presence of chloride ions would produce insoluble silver chloride salts. Lead would be found as insoluble forms attached to organic or inorganic particles, soluble chelates, or as insoluble inorganic complexes (Riley and Chester 1971; Goldberg 1975; Jernelov 1974). Arsenic is toxic in the plus-three (As_{+3}), while the plus-five (As_{+5}) is nontoxic. In areas of high arsenic discharge, organisms will convert the As_{+5} into organic-arsenic (Jernelov 1974). Copper in the plus-one state (Cu_{+1}) is a biocidal material and is used in antifouling paints. However, in marine environments, 99.9% is present in the nontoxic plus-two state (Cu_{+2}). Copper is not known to bioaccumulate (Jernelov 1974).

Of special concern are refractory organic compounds, such as the halogenated organics and polycyclic aromatics. In the most general terms, from a bioactivity perspective the halogenated organics and polycyclic aromatics are lipid-soluble materials and tend to accumulate in fatty tissues in animals. However, as the lipid-soluble organics are weakly soluble in water, especially high-ionic strength seawater, their mobility is limited. Lipid-soluble compounds tend to accumulate on the surfaces of fine particles in water, and stay on the particles. Thus, silt- and clay-sized particles (with high surface area-to-volume ratios) are effective in sorbing lipid-soluble organics.

If the sediments are ingested by deposit-feeding animals, sorbed organics could be assimilated and enter the deep-sea food web (see Section 5.4.1, **Numerical Simulations of Deep-Sea Food Chains**). Many bottom-dwelling deposit feeders consume bacteria contained in sediments. Bacteria may mobilize selected refractory organics from emplaced wastes (at unknown rates in the deep sea), accumulate these organics in lipid-rich cell walls, and thus pass the organics into the local food web as the bacteria are assimilated by sediment feeders.

Costello and Read (1994) review and summarize extensive research on the effects of sewage sludge on marine biota. Their review, which focuses on shallow-water ecosystems, can provide only general guidance as to potentially analogous situations on the abyssal seafloor. They report that sewage sludge has been shown to be toxic (though from unspecified toxins) to a wide variety of marine species as adults, juveniles, larvae, embryos, and gametes. Chronic, low-level exposure to sludge causes such conditions as fin rot in fishes and shell diseases in crabs, and produces repopulation of benthic communities by large numbers of sludge-resistant or sludge-tolerant organisms. Reversal of such effects after cessation of waste disposal, which occurs within years in shallow-water ecosystems, may

take a much longer time in the abyssal ocean (see Section 5.4.2, **Effects on Benthic Ecosystems by Disposal of Wastes on the Abyssal Seafloor**). Note that for containerized material placed on the abyssal seafloor, the potential effects mentioned above may be less severe, or have a delayed onset time, as the container deteriorates.

Hill (1967) and Menzie (1972) examined the degradation of selected pesticides under aerobic and anaerobic conditions, but did not specifically discuss the effects of low temperature and high pressure on the rates of such processes. Kilgore et al. (1972) provide a broad overview of the potential for biomediated degradation of synthetic organic compounds; however, their review does not include the cold, dark, and high-pressure conditions of the abyssal ocean environment. Matsumura (1982) describes microbial and photolytic processes affecting the degradation of organics, but again, offers little insight into processes occurring on the abyssal seafloor. Matsunaga et al. (1993) examined biomediated degradation of polychlorobiphenyls, but provides only general guidance about what could occur in the deep sea. Much research (e.g., Coats 1991; Klopffer 1992) has focused on photolytic degradation of pesticides and organic matter, which is inapplicable to the perpetually dark abyssal ocean. It appears necessary to design and apply new experimental protocols that reexamine the results by these and other researchers under conditions of the abyssal ocean.

Bacteria will probably be the first organisms that degrade organic matter of emplaced wastes in the abyssal ocean. In anoxic conditions devoid of sulfate, methane is a major byproduct of the bacterial mineralization of organic matter. Localized natural (e.g., fjords) or impacted (e.g., offshore municipal sewage outfalls) marine environments occur where sufficient organic matter has accumulated so that sulfate is locally depleted, and anaerobic fermentation of organic carbon proceeds to the release of methane gas. (Games and Hayes (1976) provide an extensive discussion of such processes in both sulfate-poor fresh water and sulfate-rich seawater.) On the abyssal seafloor, a deep mass of emplaced wastes may eventually go anoxic and become sulfate-depleted so that anaerobic fermentation could release methane (see Section 5.3.4, **Predictions of Near- and Far-Field Effects Resulting from Introduction of Wastes to Abyssal Environments**). The released methane could percolate through the waste mass, where it could serve as a carbon source for an oxic bacterial community residing on the exterior of the mass, or be carried away by the local bottom currents (see Section 5.3.2, **Geochemical Diagenesis of Emplaced Wastes**). There is also the possibility that enough methane may arise locally to form methane clathrates (see Section 5.3.5, **Potential for Formation of Methane Hydrate Clathrate within Waste Deposited on the Abyssal Seafloor**).

Understanding and predicting the impact of wastes emplaced on the abyssal seafloor as extrapolated from shallow-water marine examples is limited by what is known of biogeochemical processes under high pressure, low temperature, and aphotic conditions. The emplacement of high organic content materials on the abyssal seafloor in layer thicknesses of a few to several meters or in containers of such dimension would slow the release of waste components to the deep-sea food web and would alter the local oxic/anoxic balance affecting geochemical processes.

5.3.4 Predictions of Near- and Far-Field Effects Resulting from Introduction of Wastes to Abyssal Environments *by Richard A. Jahnke*

The introduction of large quantities of reactive sewage sludge and dredged materials on the abyssal seafloor will dramatically alter the geochemical characteristics of the deposition site. Aside from the simple burial of the natural sediment surface below the waste material, the major geochemical changes will be driven by the decomposition of the deposited reactive organic matter. To examine the potential influence of waste isolation on the abyssal seafloor, therefore, a numerical simulation of organic matter remineralization was developed. This calculation is meant to provide a quantitative framework in which to discuss the impacts of waste disposal and to identify the diagenetic and physical processes which influence these impacts. Within this framework, we also identify the major sources of uncertainty in the predicted impacts and suggest future topics of study that would improve this simulation.

5.3.4.1 Model Description

The processes represented in the numerical simulation are schematically depicted in Figure 5.3.4-1. The model development here parallels that given in Jahnke et al. (1982, 1994) and has been expanded to include sulfate reduction, fermentation and methane, and sulfide and ammonium oxidation reactions. Basically, the rate and equilibrium constants for reactions and initial concentration distributions are specified. Distributions that are in steady state with the estimated natural input fluxes are used as the initial conditions. Inputs of organic and inorganic particles may then be varied and the resulting variations in chemical distributions calculated.

Sediment mixing is assumed to be a random, diffusion-like process parameterized by a single biodiffusion coefficient. To reflect the general decrease in macrobenthic abundance with sediment depth, mixing rates below 10-cm depth are assumed to be one-tenth that of the surface layer. Because the extremely high deposition rates that occur during waste input will tend to bury the macrobenthic organisms responsible for mixing the sediments, we assume that mixing will be much less during the actual input period. We, therefore, fix the mixing rate during waste deposition at one-tenth the natural value. We also assume that once deposition is halted and the sediments accumulate at their natural rate, macrobenthic organisms will repopulate the location and mixing will return to natural rates. The rate of recovery is currently unknown and the simulation presented here assumes the recovery is instantaneous.

Sediment burial is parameterized as an advective process, progressively burying particles below the sediment surface. The initial rate of burial is determined by the input of carbonate and noncarbonate particles and the porosity of the surface sediments. For the calculations presented here, we assume a surface porosity of 80%. As porosity decreases with increasing sediment depth due to compaction, the rate of particle advection also decreases. In addition, dissolution of calcium carbonate particles also decreases the net burial rate.

We assume that organic matter may be oxidized using oxygen, nitrate, or sulfate as the terminal electron acceptor. These processes will occur in the order of greatest free energy release. That is, in the presence of oxygen, oxygen reduction will be the dominant

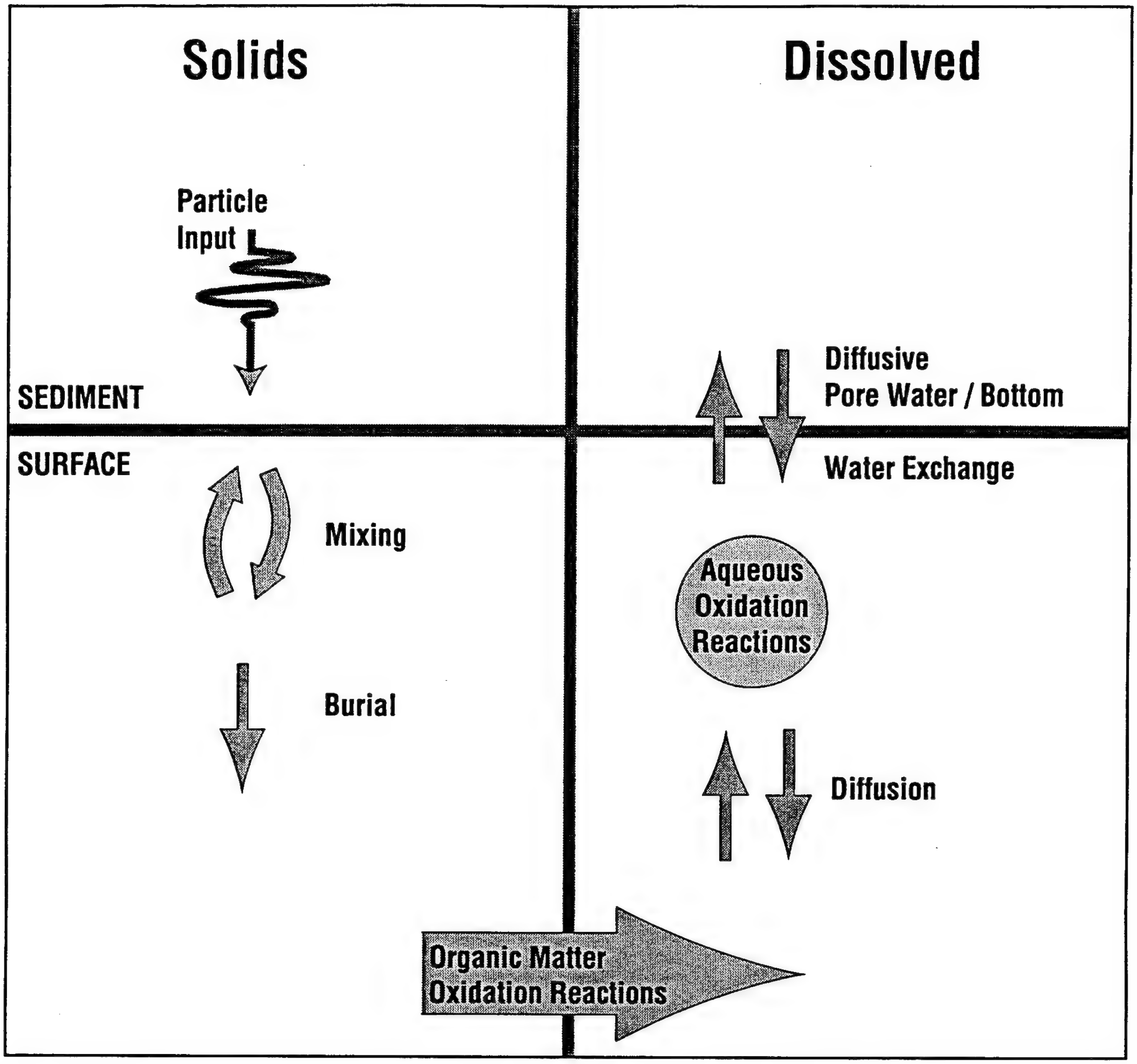


Figure 5.3.4-1. Schematic representation of transport processes and reactions considered in the waste deposition/remineralization simulation.

remineralization pathway. When oxygen is essentially no longer available, nitrate reduction will dominate. When both oxygen and nitrate are depleted, sulfate reduction will dominate. Finally, when no inorganic oxidants are available, remineralization will continue by fermentation. These organic matter oxidation reactions are summarized in Table 5.3.4-1.

We assume that the rate of remineralization is proportional to the amount of organic carbon available. Because the waste material is deposited very rapidly, we assume that the reactivity of the organic matter is the same throughout the deposit. Thus, the remineralization of the organic matter is parameterized as a first-order process in all reaction zones. In most of the following simulations, the half-life of the reactive organic matter is assumed to be 50 years. To assess the sensitivity of the results to this assumption, additional simulations using a half-life of the reactive organic matter of 5 years were also run. Examples of these results are presented as indicated for comparison.

The pore-water solutes are allowed to diffuse freely through the pore waters and to exchange with the overlying bottom waters. In each case, the molecular diffusion coefficient for each chemical species has been adjusted for sediment tortuosity using the Archie relationship with an assumed exponent of 2 and a porosity of 80%. The dissolved carbonate system is maintained in equilibrium. Calcium carbonate dissolution rates are represented by the saturation state raised to a power of 4.5 times a rate constant of 5%/day (Jahnke et al. 1994).

Reduced solutes produced during fermentation and sulfate reduction may also be oxidized if they encounter the appropriate oxidant. Methane may be oxidized by sulfate, nitrate, or oxygen. Ammonium and sulfide may be oxidized by nitrate or oxygen. The dominant aqueous oxidation reactions are also summarized in Table 5.3.4-1.

5.3.4.2 Input Constraints

The characteristics of the waste inputs for the simulation are summarized in Table 5.3.4-2. We assume waste will be deposited at a test site for one year. During this year, a total of 4.5×10^6 m^3 (6×10^6 yd^3) of dredged material and one million tons (dry weight) of sewage sludge will be deposited. At the indicated density and porosities, this corresponds to a total input of 3.8×10^{12} g (or 8.5 million m^3) of waste material. If deposition is evenly distributed throughout the year, this corresponds to a daily input of 2.3×10^4 m^3. For purposes of this calculation it is assumed that the sewage sludge contains approximately 30% organic carbon and the dredged material has none. (This assumption of no organic carbon in the dredged material is unrealistic, but when the dredged material is treated together with the sewage sludge, the assumption provides a reasonable organic carbon content for a combined waste.) The combined waste material will contain approximately 7.9% organic carbon.

For the simulation, it is assumed that input is continuous throughout the year and that it occurs at a specific point on the seafloor. This will result in a deposit in the shape of a cone as depicted in Figure 5.3.4-2. This figure was calculated assuming that the final slope of the deposit is maintained at 2°. Note that the vertical exaggeration of the figure is 20:1.

Table 5.3.4-1 Dominant Aqueous Oxidation Reactions

Organic Matter Oxidation Reactions
$(CH_2O)_{106}\ (NH_3)_{16} + 106\ O_2 \rightarrow 106\ CO_2 + 16\ NH_3 + H_2O$
$(CH_2O)_{106}\ (NH_3)_{16} + 84.8\ O_2\ HNO_3 \rightarrow 106\ CO_2 + 42.4\ N_2 + 16\ NH_3 + 148.4H_2O$
$(CH_2O)_{106}\ (NH_3)_{16} + 53\ SO_4^{2-} \rightarrow 106\ CO_2 + 53\ S^{2-} + 16\ NH_3 + 106\ H_2O$
$(CH_2O)_{106}\ (NH_3)_{16} \rightarrow 53\ CO_2 + 53\ CH_4 + 16\ NH_3$
Aqueous Oxidation Reactions
$16\ NH_3 + 32\ O_2 \rightarrow 16\ HNO_3 + 16\ H_2O$
$5\ NH_3 + 3\ HNO_3 \rightarrow 4\ N_2 + 9\ H_2O$
$HS + 2\ O_2 \rightarrow HSO_4^-$
$CH_4 + SO_4^{2-} \rightarrow S^{2-} + CO_2 + H_2O$

Table 5.3.4-2. Waste Input Characteristics

	Dredge	Sewage	Total
Input (g/yr)	$2.8x10^{12}$	$1x10^{12}$	$3.8x10^{12}$
Denisty (g/cm^3)	2.5	1.25	-
Porosity (%)	75	80	-
Input Vol. (m^3)	$4.5x10^6$	$4x10^6$	$8.5x10^6$
Equivalent Daily Rate of Input (m^3/day)	$1.2x10^4$	$1.1x10^4$	$2.3x10^4$
Organic C Content (%)	-	30	7.9

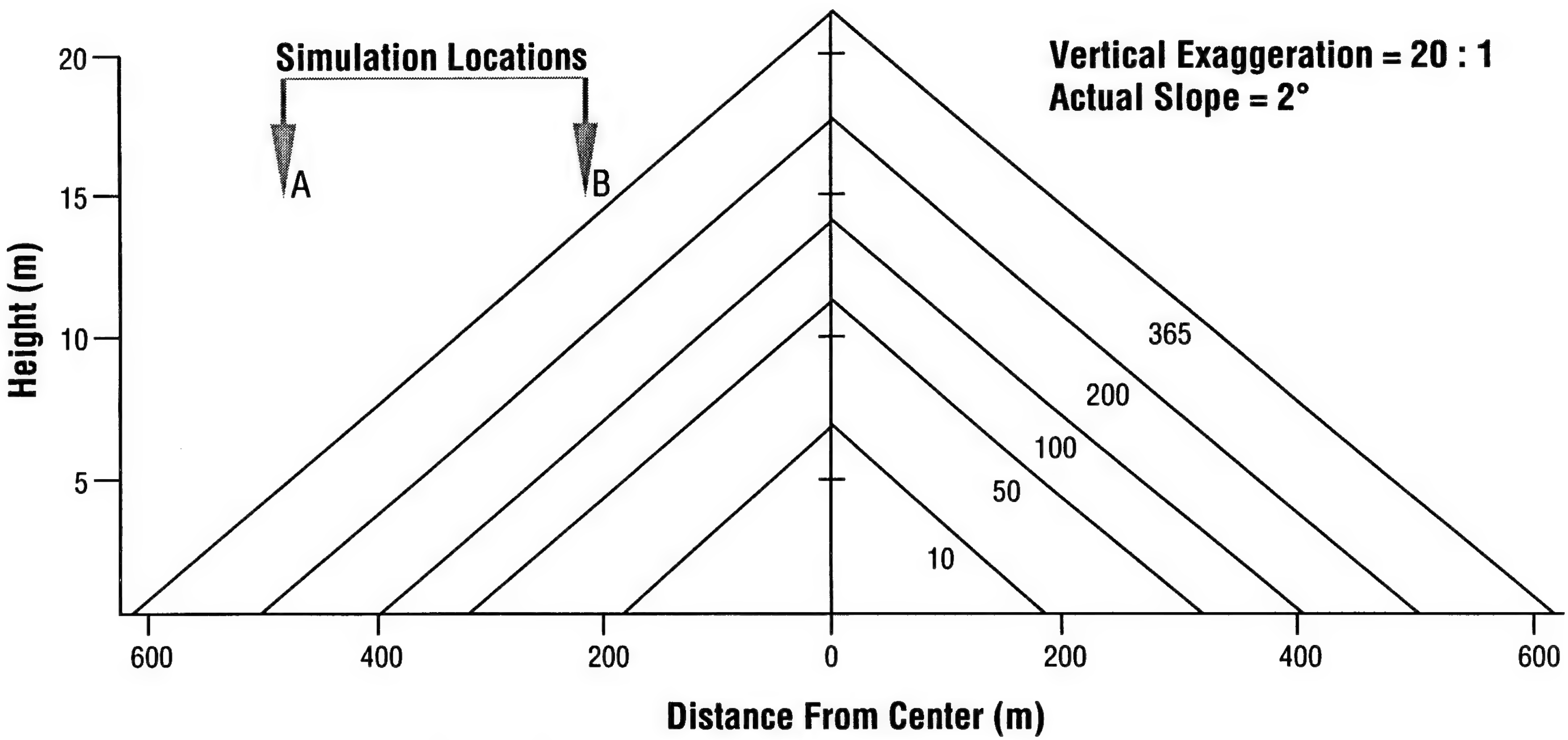


Figure 5.3.4-2. Schematic of the waste deposit geometry. Numbers indicate the number of days of input required to reach each line.

During the initial disposal, the thickness of the deposit grows rapidly. After only 10 days of input, the center of the deposit is more than 6 m thick. However, as the area of the base grows, the rate of growth for the height of the waste pile slows. Thus, while a pile 6 m thick at the center is formed within the first 10 days of deposition, the final 165 days of input adds only 4 m. This slowing of the daily accumulation is quantitatively displayed in Figure 5.3.4-3. It is readily observable that after 100 days of input, the waste accumulates at rates less than 5 cm/day. By the end of the year, however, the base of the deposit has grown to over 1.2 km in diameter (Fig. 5.3.4-2).

The simulations that follow were calculated for two locations within the waste pile. Location A is 500 m from the center of the deposit. It takes approximately 200 days of continuous input for the pile to grow to this diameter. Thus, during one year of waste deposition, this location receives approximately 165 days of waste input at a rate that begins at approximately 3 cm/day and ends at just under 2 cm/day (Fig. 5.3.4-3), resulting in the total accumulation of approximately 4 m waste. The majority of the calculations presented are for this location. Location B is only 200 m from the center of the deposit. This site receives approximately 345 days of input, starting at a rate of nearly 20 cm/day. The final thickness of waste at this location is nearly 14 m.

As will be discussed in the following section, the recovery of the sediment to these inputs is long relative to the actual accumulation time. Thus, the simulation also reasonably represents the situation where a waste layer was instantaneously deposited. Such a situation would occur if a close-packed layer of porous bags of waste were emplaced on the seafloor. Site A would represent bags approximately 4 m in diameter and site B would represent bags 14 m in diameter.

5.3.4.3 Results

(1) Example Deposition Simulation

The results of the numerical simulation are presented in Figures 5.3.4-4 through 5.3.4-16. To facilitate the presentation of the results, the chemical concentrations on these graphs have all been normalized to their maximum concentration. The maximum concentration for each solute is indicated on each figure. Note that the depth scale on each figure varies depending on the depth to which the influence of the waste has penetrated.

The predicted solute and particulate organic carbon (POC) distributions at site A after 10 days of waste input are displayed in Figure 5.3.4-4. As stated previously, because site A is approximately 500 m from the center of deposition, this deposition corresponds to the deposition that would occur between day 200 and day 210 of an actual 1-year-long pilot project.

After 10 days of input, a high POC layer is readily observed in the upper 0.3 m of the sediment column. The decomposition of this POC results in the nearly immediate total consumption of oxygen and nitrate in this layer. Oxygen is absent from essentially the sediment surface to a depth of 0.3 m and nitrate is absent from the sediment surface to

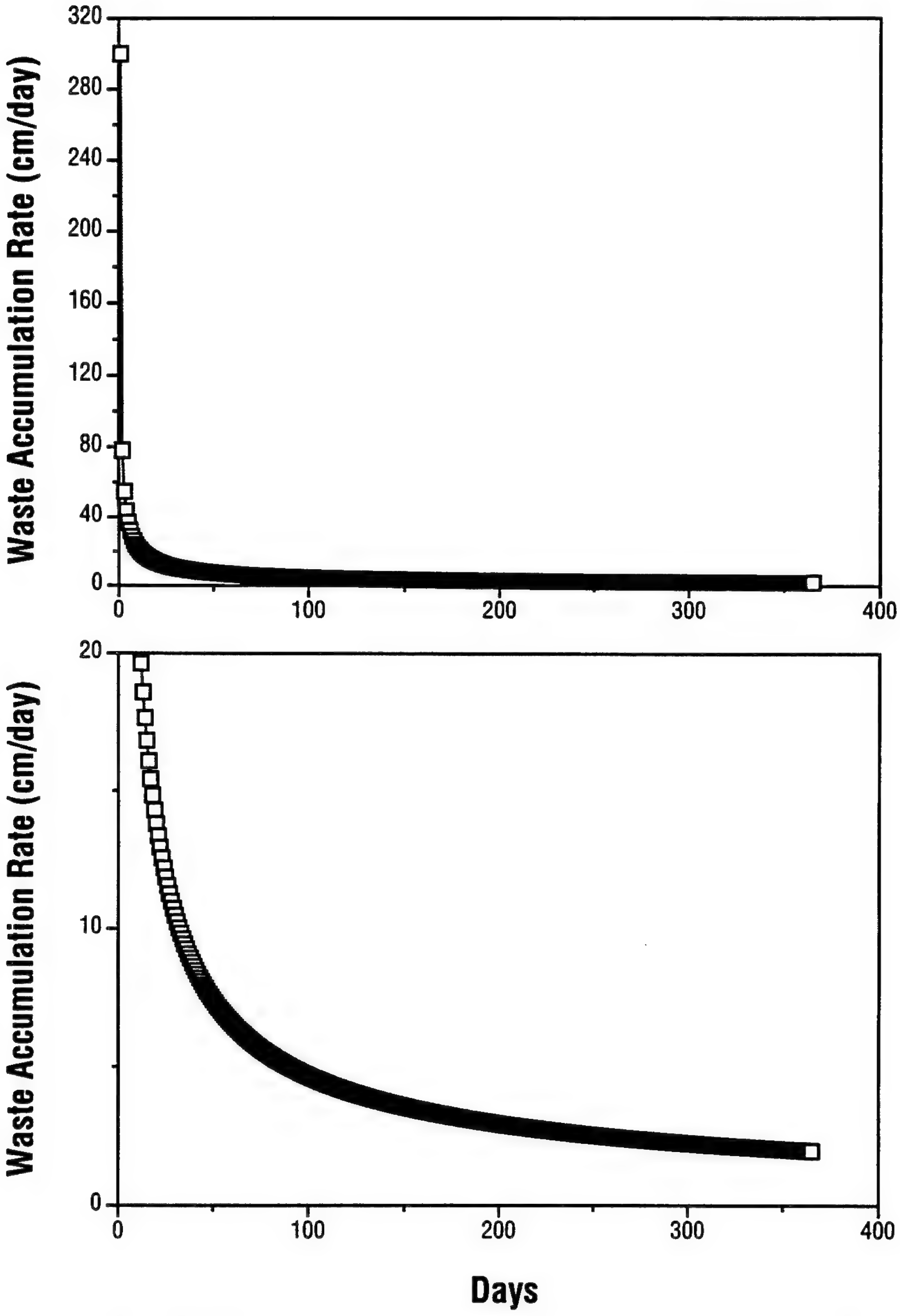


Figure 5.3.4-3. Daily waste accumulation rate as a function of time through the input year.

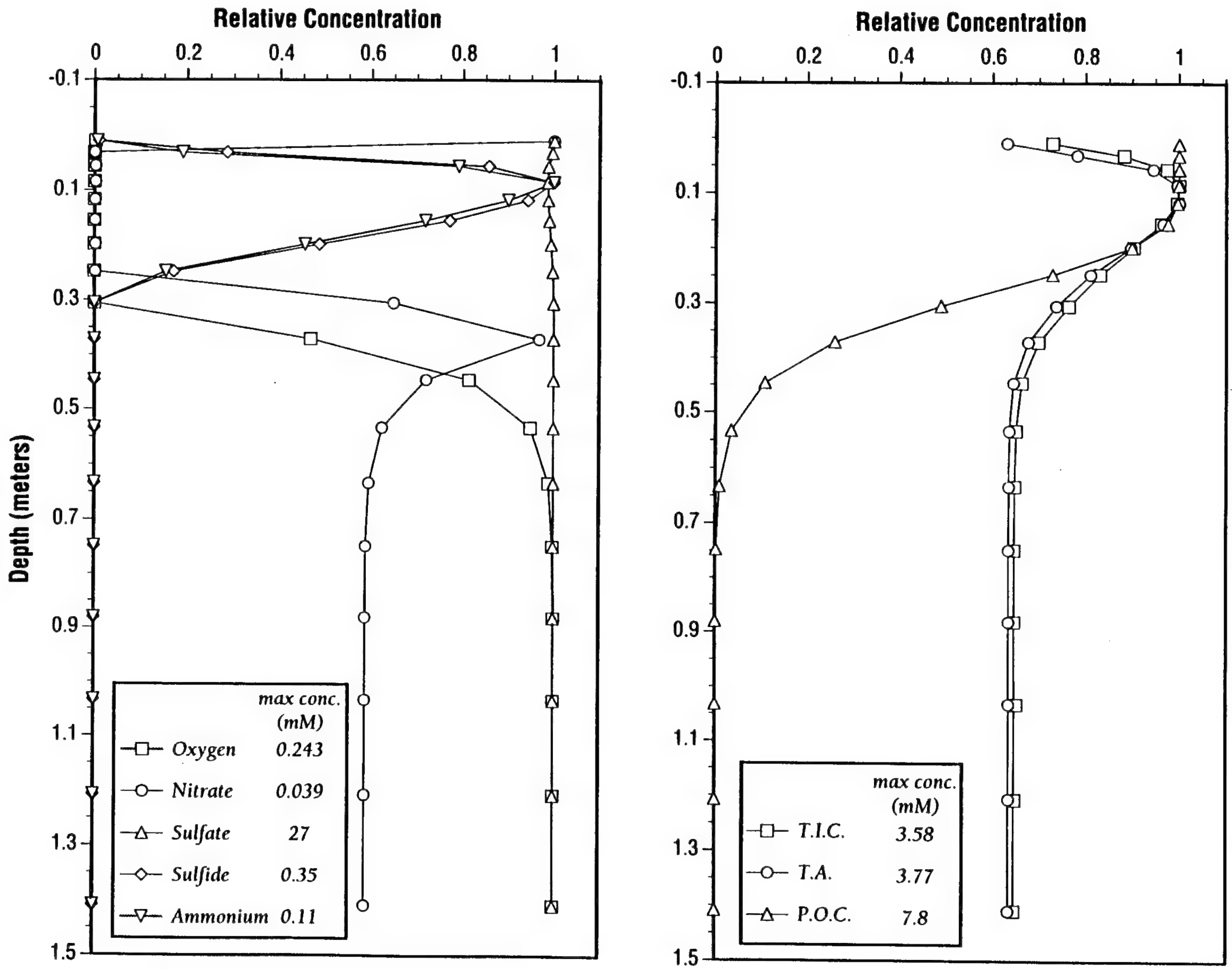


Figure 5.3.4-4. Pore water constituent and sedimentary organic carbon distributions at location A after 10 days of waste disposal.

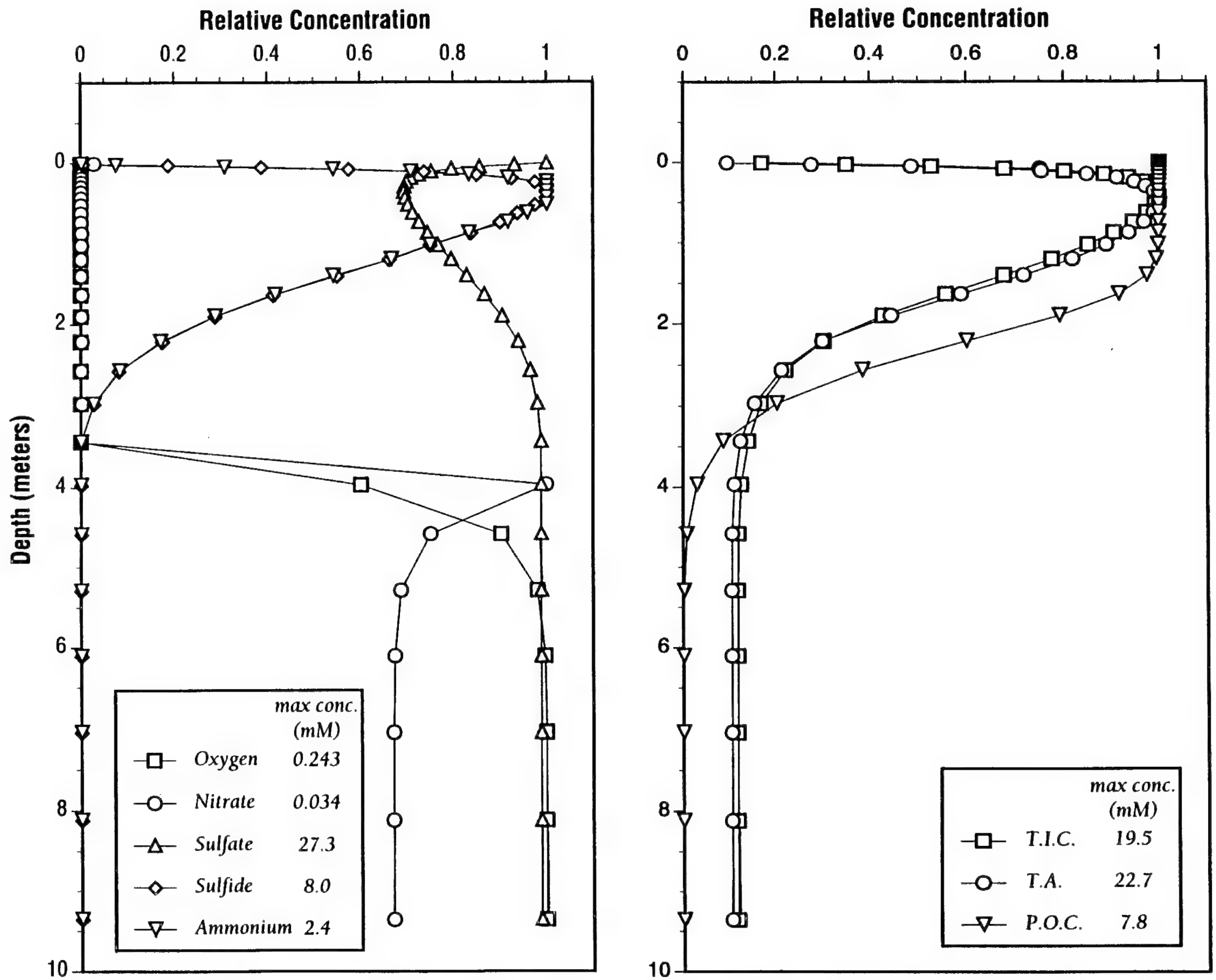


Figure 5.3.4.-5. Pore water constituent and sedimentary organic carbon distributions at location A after 100 days of waste disposal.

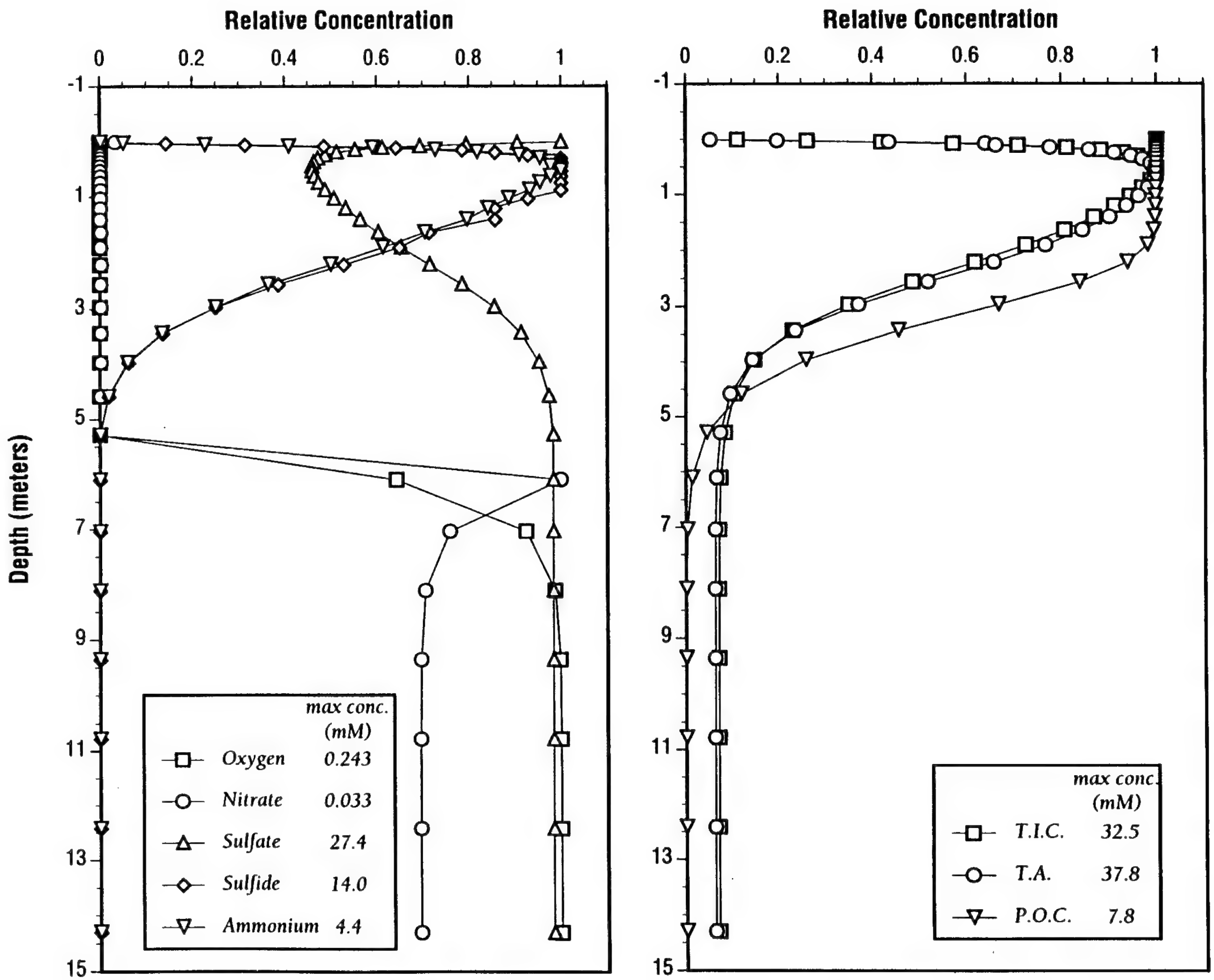


Figure 5.3.4.-6. Pore water constituent and sedimentary organic carbon distributions at location A after 165 days of waste disposal.

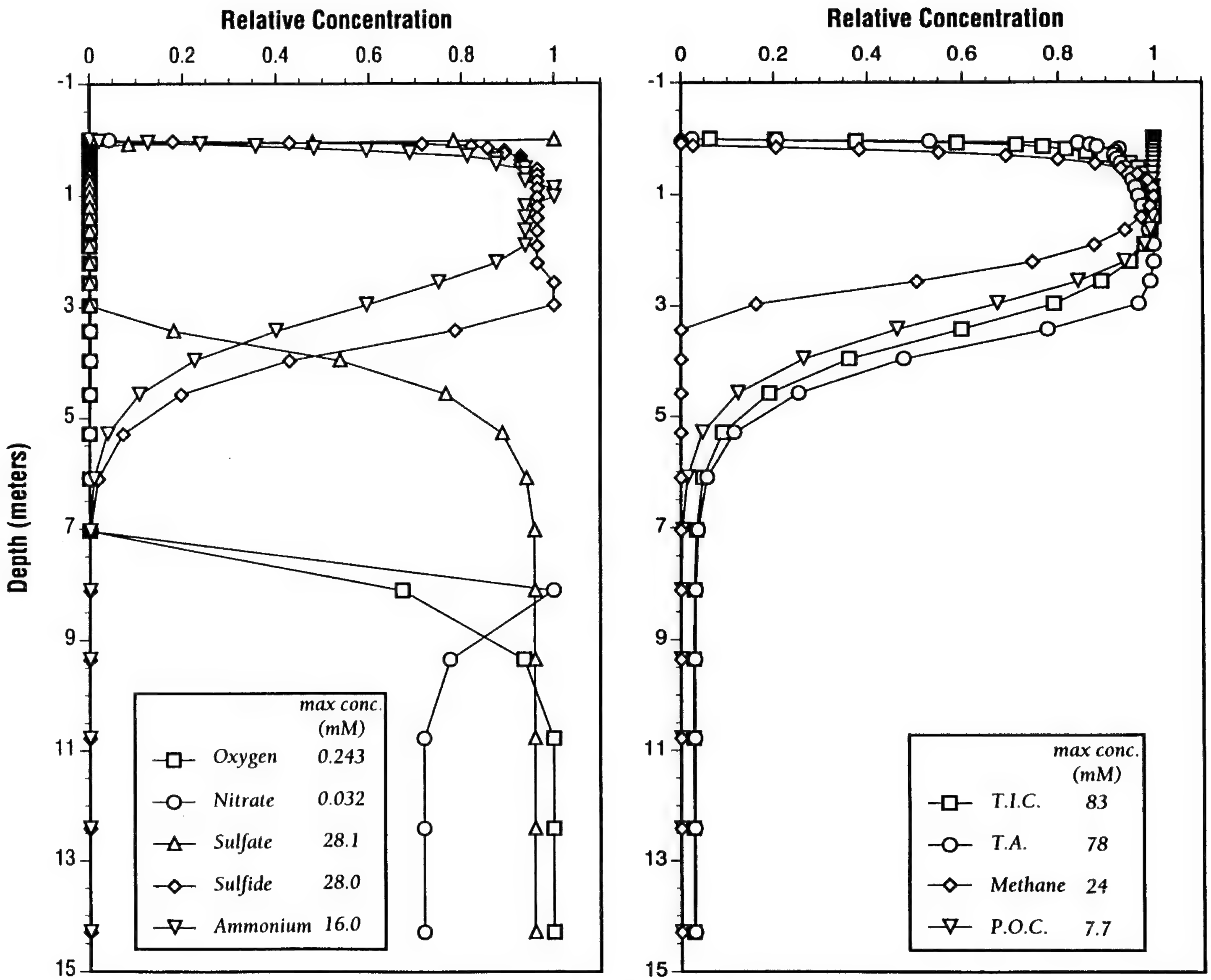


Figure 5.3.4-7. Pore water constituent and sedimentary organic carbon distributions at location A one year after cessation of waste disposal.

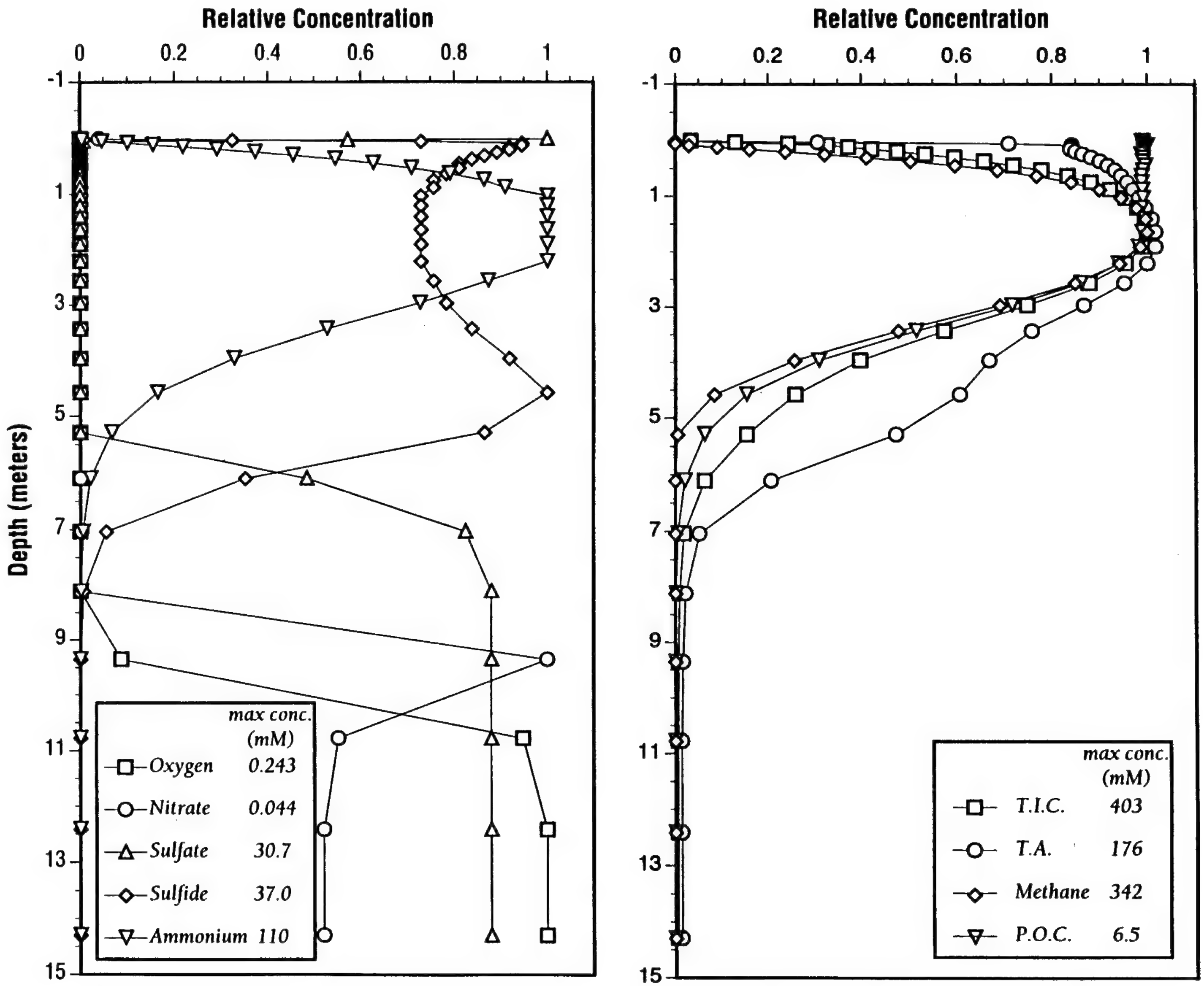


Figure 5.3.4-8. Pore water constituent and sedimentary organic carbon distributions at location A 10 years after cessation of waste input.

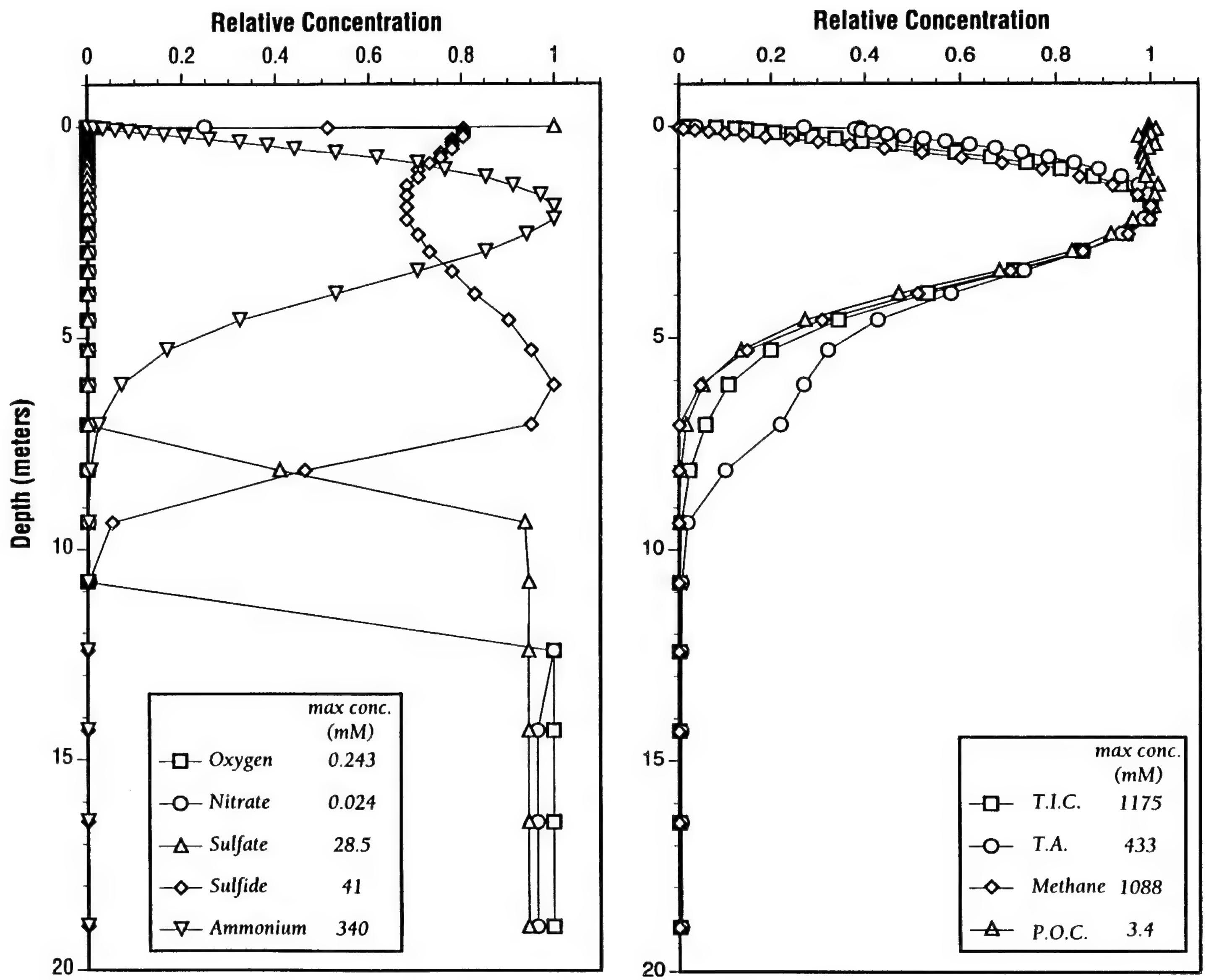


Figure 5.3.4-9. Pore water constituent and sedimentary organic carbon distributions at location A 50 years after cessation of waste input.

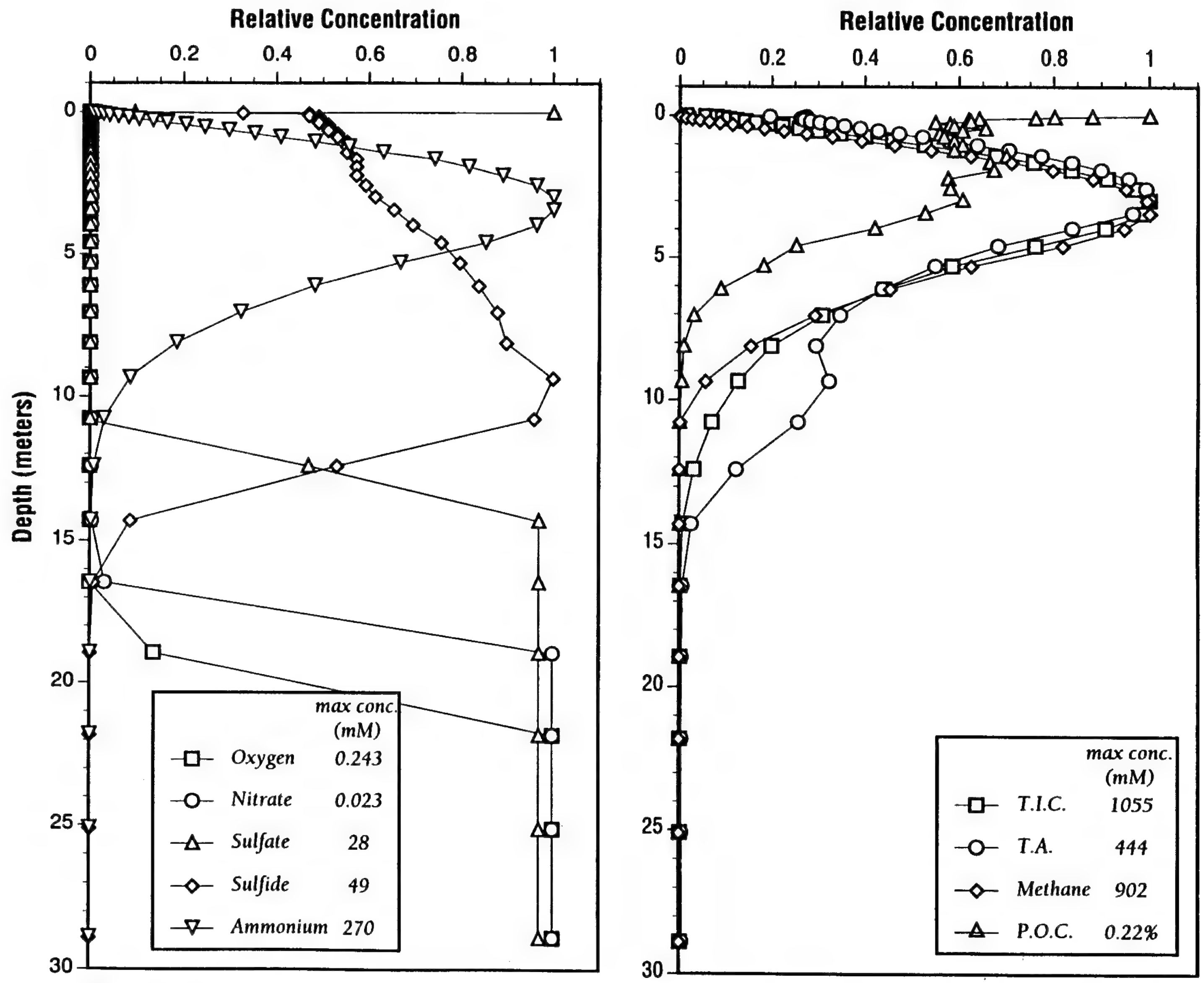


Figure 5.3.4-10. Pore water constituent and sedimentary organic carbon distributions at location A 275 years after cessation of waste input.

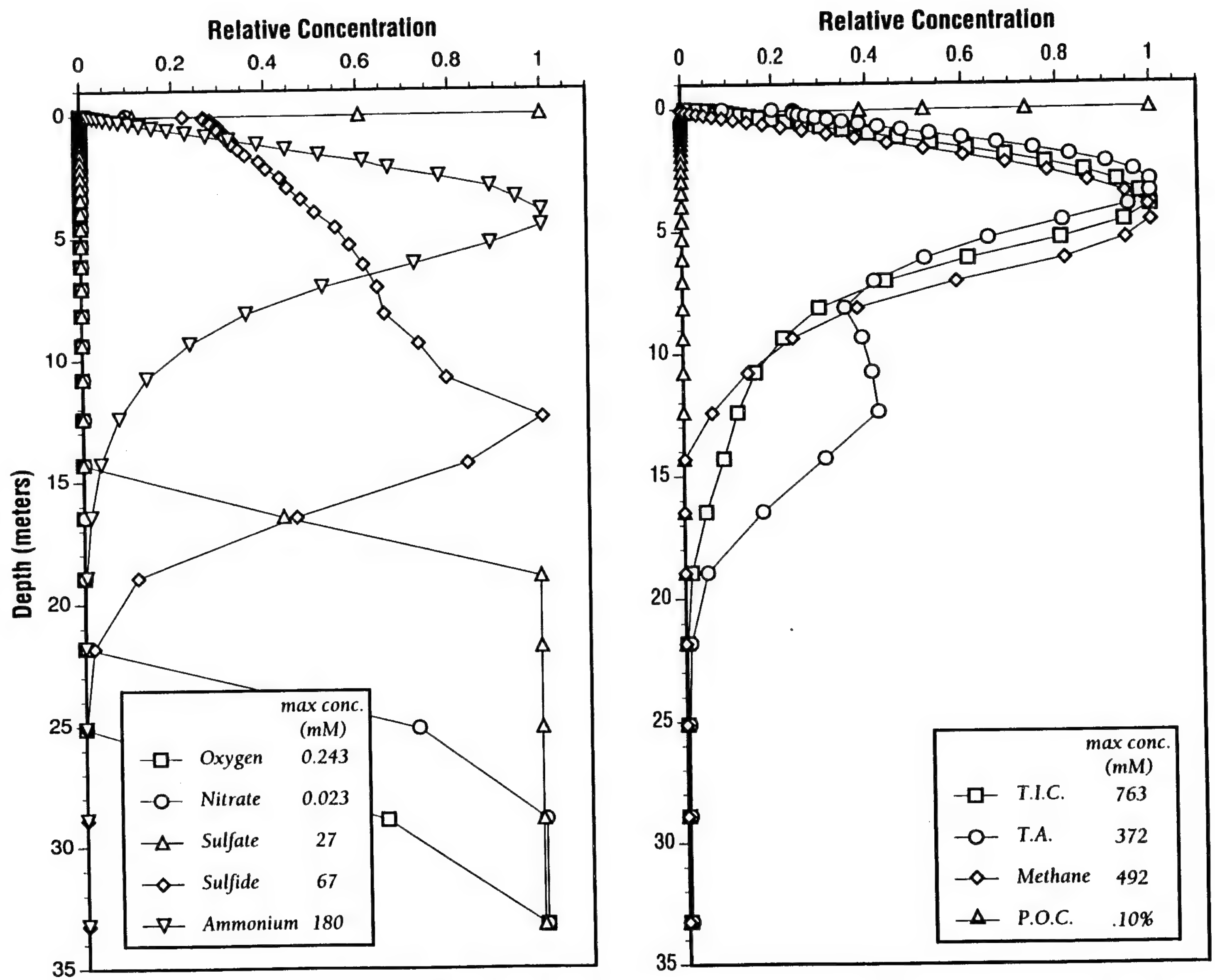


Figure 5.3.4-11. Pore water constituent and sedimentary organic carbon distributions at location A 725 years after cessation of waste input.

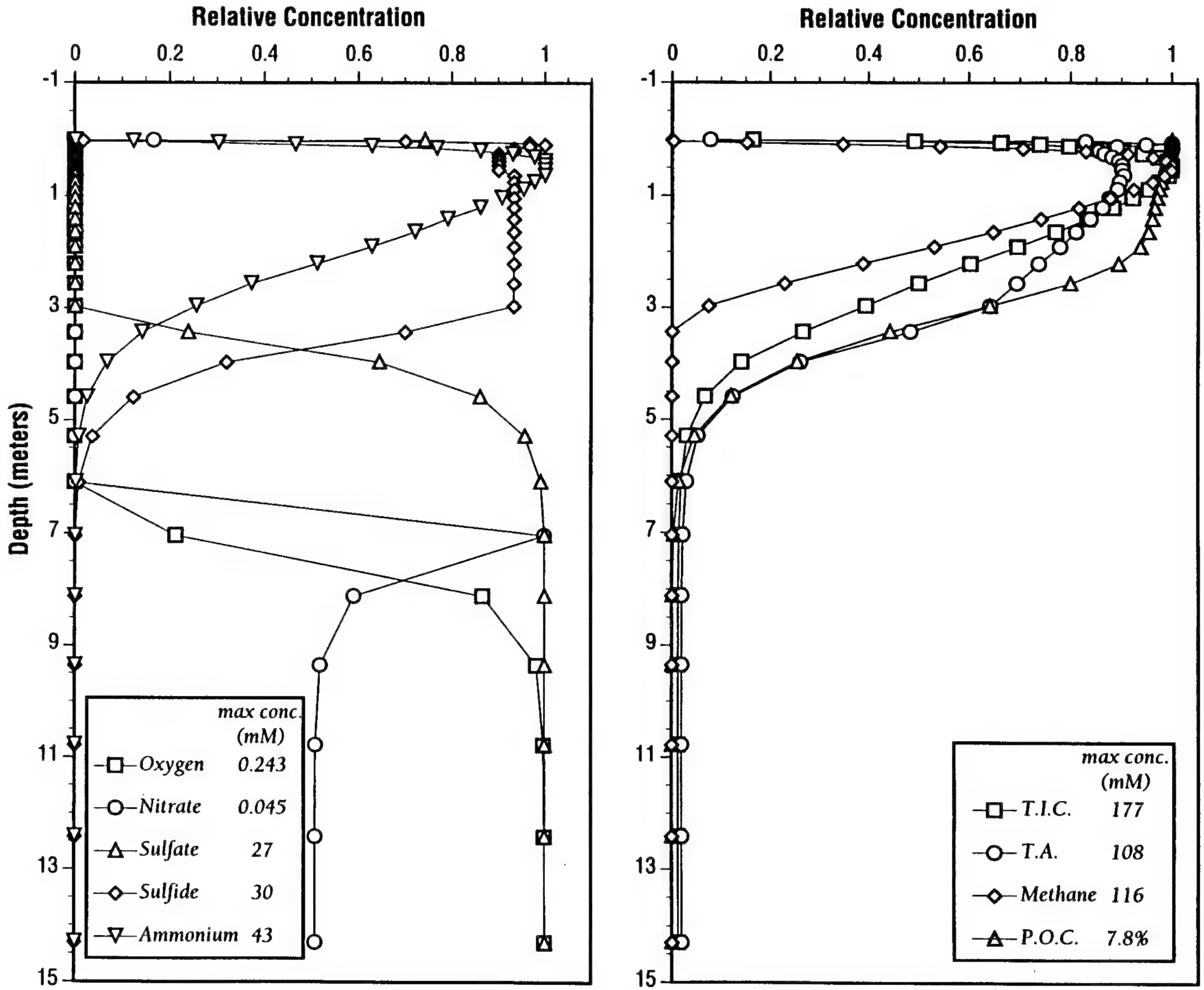


Figure 5.3.4-12. Pore water constituent and sedimentary organic carbon distributions at location A after 165 days of waste disposal with an organic matter half-life of 5 years.

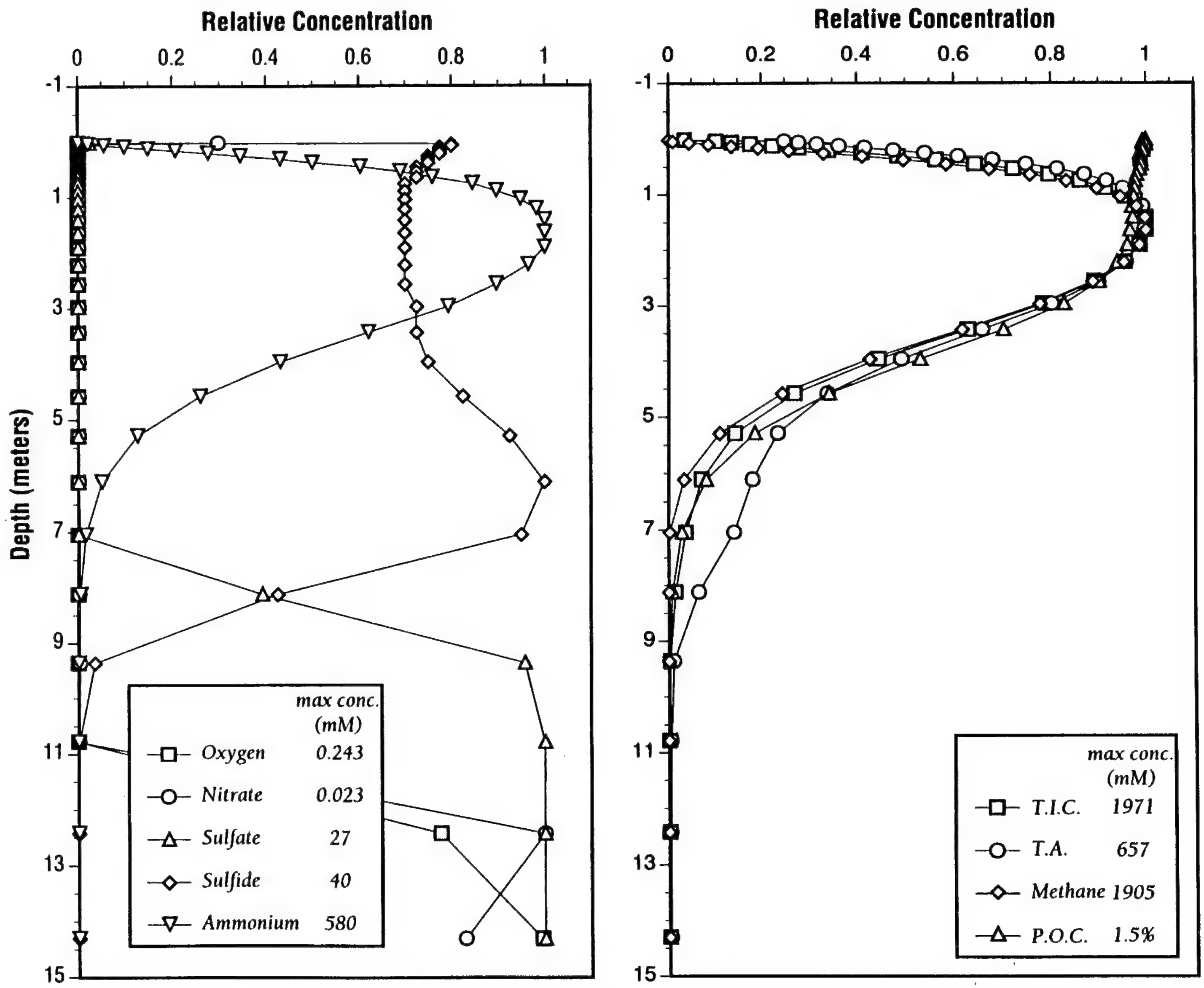


Figure 5.3.4-13. Pore water constituent and sedimentary organic carbon distributions at location A 10 years after cessation of waste input with a half-life of 5 years.

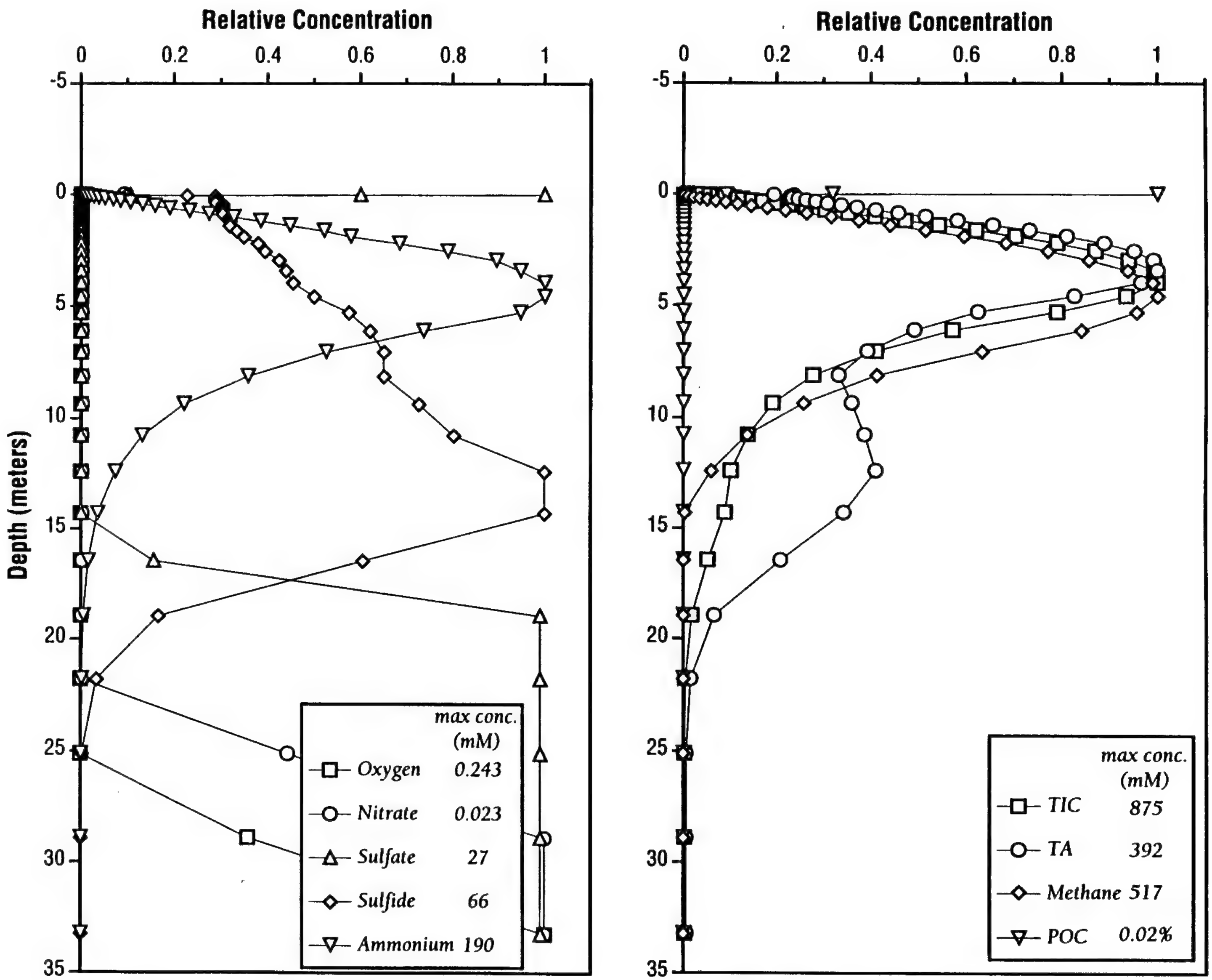


Figure 5.3.4-14. Pore water constituent and sedimentary organic carbon distributions at location A 725 years after the cessation of waste input with a half-life of 5 years.

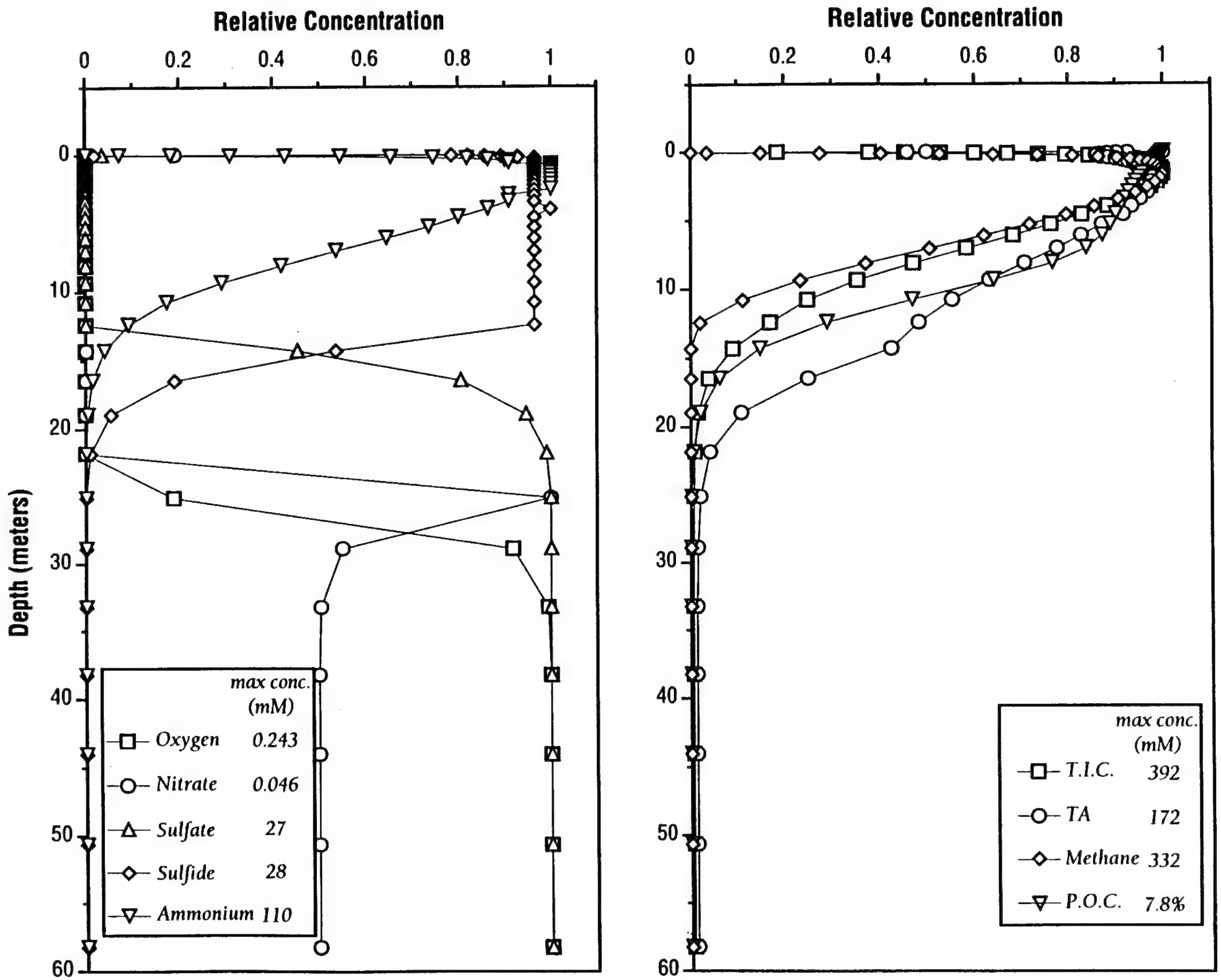


Figure 5.3.4-15. Pore water constituent and sedimentary organic carbon distributions at location B after 345 days of waste input.

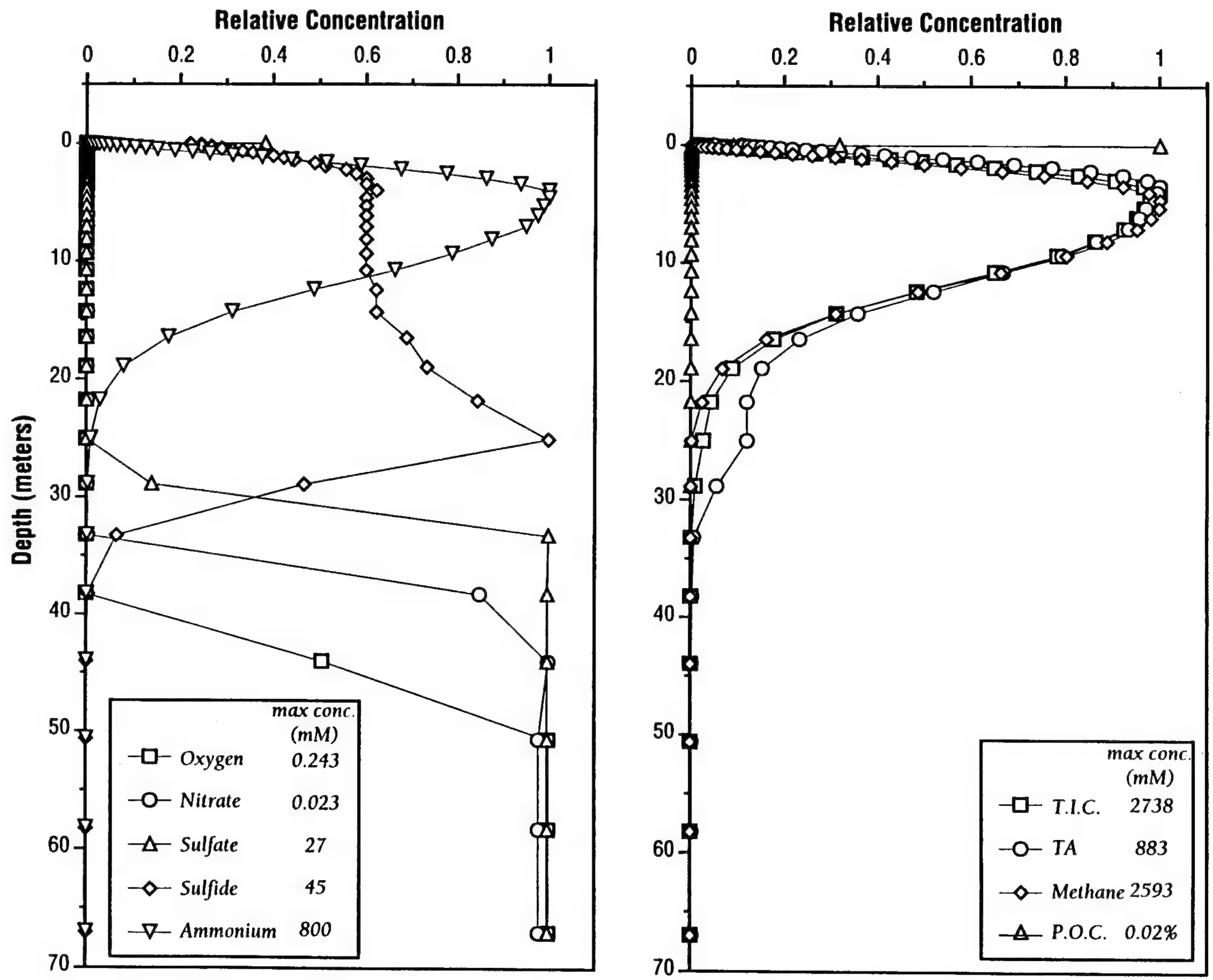


Figure 5.3.4-16. Pore water constituent and sedimentary organic carbon distributions at location B 275 years after cessation of waste input.

approximately 0.25 m. Elevated levels of ammonium and sulfide are present in this layer. Note that the peak in nitrate at approximately 0.4 m is produced by the oxidation of the ammonium diffusing downward from the waste layer by pore-water oxygen. Elevated values of Total Inorganic Carbon (TIC) and Titration Alkalinity (TA) in the waste layer are also calculated. Note that despite these large pore-water chemical changes, the maximum POC is essentially at its input value of 7.9%.

After 100 days of waste input (Fig. 5.3.4-5), the high POC layer has grown to approximately 3 m. Note the scale change of the vertical axis. This layer is again characterized by elevated sulfide, ammonium, TIC, and TA levels, and the complete absence of oxygen and nitrate. At this point, a significant depletion of sulfate in the waste layer is also observed.

Figure 5.3.4-6 displays the calculated distributions after 165 days of deposition, which at site A would represent the end of a 1-year pilot experiment. Note that the vertical scale has been expanded again and now represents the upper 15 m of the sediment column. In general, the profile shapes are similar to the previous figure. The high POC, zero-oxygen and zero nitrate layer has grown to 4–5 m thickness. Sulfate is becoming even more depleted in this layer with values reaching less than half of the initial bottom-water and pore-water value. Again, even though large changes are occurring in the pore-water chemistry and redox state, POC values are still near the input level.

One year after the cessation of deposition (Fig. 5.3.4-7), POC levels in the waste layer have only decreased slightly. Continued decomposition of this material has fully exhausted the available sulfate in the layer and initiated fermentation with the associated production of methane and ammonium. Diffusion of this ammonium and sulfide into the pelagic sediments has extended the zone of zero oxygen and nitrate to a depth of 7 m.

Ten years after cessation of waste input (Fig. 5.3.4-8), the oxygen- and nitrate-depleted layer has expanded to a depth of 8 m and sulfate is depleted in the upper 5.5 m. The principal pathway by which the waste organic matter is decomposing is via fermentation, and maximum methane levels have dramatically increased. Because all of the available sulfate within the waste layer has been reduced to sulfide, sulfide levels in the middle of the layer do not increase dramatically. However, sulfate from bottom water and from deeper in the pore waters diffuses along the concentration gradient toward the reacting layer where it is reduced to sulfide either by reaction with the decomposing organic matter or via anaerobic methane oxidation (see Table 5.3.4-1). Thus, additional sulfide is produced at the top and bottom of the reacting layer, resulting in the dual maxima profile observed. Maximum POC levels have now dropped to 6.5%.

Fifty years after the cessation of waste input (Fig. 5.3.4-9), the sulfate-depleted layer has expanded to nearly 7 m depth and the oxygen- and nitrate-depleted layer is over 11 m thick. The former is due to the downward diffusion of methane and the latter is due primarily to the downward diffusion of sulfide. The sulfide profile still exhibits a dual maxima, although they are asymmetrical, with the deeper maximum being larger. Maximum POC values have dropped to approximately half the input value. This is a direct result of the assumed organic matter half-life of 50 years. Note that the maximum concentration is not exactly half of the initial value due to dilution with lower POC sediment by particle mixing.

Methane and TIC concentrations have reached extremely high values, potentially exceeding levels at which gas hydrates may form (see Section 5.3.4.4, **Discussion**).

After 275 years, altered pore-water gradients are calculated to penetrate to greater than 20 m into the sediments (Fig. 5.3.4-10). The oxygen-depleted layer is greater than 16 m thick and the sulfate-depleted layer is greater than 11 m thick. The sulfide layer has grown to a thickness of greater than 15 m but has lost its dual maxima shape due to the increased loss of sulfide near the sediment surface from the increased penetration of oxygen and nitrate into the sediments. POC values have reached very low levels. The diagenetic processes are being driven by the oxidation of residual methane and ammonium. Since methane oxidation results in the production of sulfide, the growth of the sulfide layer is also fueled by the methane oxidation.

Thus, at this point, the original waste POC has all but disappeared. However, the anoxic layer produced by the input of waste remains and, in fact, continues to expand due to the oxidation of the methane produced. The recovery of the sediment column to its natural state, therefore, no longer depends on the reactivity of the waste material, but on the physical transport of oxidant to the anoxic layer or the transport of the reduced solutes out of the sediments.

After 725 years (Fig. 5.3.4-11), the altered pore-water profiles penetrate to nearly 35 m. Oxygen is absent in the upper 25 m and sulfate is absent from the upper 14.5 m. The sulfide-containing layer is more than 20 m thick and the maximum concentration has increased to 67 mM. This is due to the continued production of sulfide from pore-water sulfate by anaerobic methane oxidation. Maximum methane concentrations are decreasing but are still quite high.

Thus, more than 700 years after the cessation of waste input, the pore-water system is not only still significantly altered, but the thickness of the impacted layer is still growing. Extrapolating these results into the future, it is estimated that the reduced layer will take an additional 1000–2000 years to be oxidized. Reestablishing natural conditions throughout the sediment column would require an additional 20,000 to 30,000 years as molecular diffusive transport over the scale of tens of meters is extremely slow.

(2) Sensitivity to Decomposition Rates

The sensitivity of the results to the assumed reactivity of the organic matter was assessed by performing simulations where the organic matter half-life had been reduced by a factor of 10 (to 5 years). Again, the calculations were performed for site A on the hypothetical depositional cone. The simulated distributions after 165 days of waste input (i.e., the end of the input period) are presented in Figure 5.3.4-12. Unlike the previous result (Fig. 5.3.4-6), the faster reaction rate results in complete sulfate depletion and the production of methane in the upper 3 m of the sediment column. Significantly higher concentrations of TIC and ammonium in this simulation, relative to the earlier calculation, verify greater decomposition by the end of the depositional period at these faster degradation rates.

Ten years after the cessation of deposition (Fig. 5.3.4-13), POC levels have decreased significantly from their input values. This more rapid loss of POC results in higher maximum concentrations of methane, TIC, and ammonium than with the slower kinetics. These higher concentrations of reduced solutes produce larger gradients and, therefore, larger fluxes deeper into the sediments. This results in a thicker reduced layer than was calculated with the slower degradation kinetics (Fig. 5.4.3-8). Thus, the oxygen depleted layer is nearly 11 m thick in this simulation, whereas an 8–9 m thick oxygen-depleted layer was calculated for this same time at the slower reaction rates.

After 725 years (Fig. 5.3.4-14), the results obtained with the faster degradation rate constant are nearly identical to those presented earlier (Fig. 5.3.4-11). This is because once the waste POC is converted to methane, the evolution of the pore-water profiles and recovery of the sediment column is controlled by the diffusive transport and reactivity of the reactive solutes, especially methane. Thus, within broad limits, the simulation results are independent of the degradation rate of the waste POC, and the conclusions reached here are not sensitive to moderate variations in remineralization rate.

(3) Site B Simulations

The influence of a thicker waste pile is examined by simulating the distributions at location B on the hypothetical depositional cone (see Fig. 5.3.4-2). During a 1-year pilot experiment, waste accumulation occurs for 345 days at this site, eventually producing a waste layer approximately 14 m thick.

The calculated distributions at the end of the depositional period are displayed in Figure 5.3.4-15. The overall shapes of the profiles and major features are similar to those already discussed for site A. With the longer accumulation period and thicker waste layer, the changes in concentrations tend to be larger than at site A. Also, complete sulfate depletion occurs in the upper 12 m of the sediment column and methane is produced.

The calculated profiles 275 years after the cessation of waste input are presented in Figure 5.3.4-16. While the profile shapes are similar to those calculated for site A, the layer of altered concentrations extends more than 45 m into the sediments. Maximum methane, TIC, TA, and ammonium concentrations are also much greater at site B. It is important to note, however, that the maximum sulfide values at sites A and B are nearly the same. This is because in both cases the dominant source of sulfate for sulfate reduction is seawater and pore-water sulfate. Once it is all converted to sulfide, decomposition continues through fermentation, and the sulfide levels increase only slowly due to sulfate reduction at the upper and lower boundaries of the reactive layer. Thus, at site B, a much higher proportion of the waste POC decomposes via fermentation than at site A. The amount of sulfide available to sequester trace metals per unit of waste is greater at site A.

5.3.4.4 Discussion

As with all models of this type, it may be said that essentially all aspects of the model are wrong or inaccurate to some degree. The purpose of presenting this simulation is to

provide a quantitative framework for discussing the geochemical issues related to waste isolation, establish initial relationships between inputs and geochemical results, and identify the major gaps in our knowledge that prevent a more accurate geochemical assessment of the impacts of placing waste on the abyssal seafloor. Despite the limitations, several observations can be made based on these calculations.

(1) Formation of Sulfide as a Mechanism for Immobilizing Trace Metals

The majority of toxic trace metals contained in waste materials form insoluble sulfide solid phases. In near-shore and estuarine systems, the mobility and accessibility of toxic metals to benthic organisms has been assessed by determining the availability of acid volatile sulfides (AVS). If AVS exceeds the combined concentrations of toxic metals, it is concluded that the metals are immobilized and generally not available for uptake by benthic organisms (Casas and Crecilius 1994; Allen et al. 1993). Thus, from this perspective, it is important to make sure that sufficient sulfide is produced by sulfate reduction to immobilize the trace metals.

As demonstrated by the preceding calculations, the waste organic input at both site A and B is sufficient to completely exhaust the available sulfate. Decomposition and presumed release of associated toxic metals, then continues via fermentation which does not directly result in the production of sulfide. Thus, depending on the metal content of the waste material, it may be possible for the metal release to exceed the sulfide production. If this occurs, the excess metals will be more mobile and available for uptake by benthic organisms.

The extent to which total decomposition and, hence, trace metal release, may exceed sulfide production depends on the proportion of the organic material that is remineralized via fermentation. The greater the role that fermentation plays, the greater the possibility that there will be insufficient sulfide to immobilize the trace elements. As can be observed by comparing the maximum concentrations of sulfide and methane 275 years after the cessation of waste input at sites A and B (Figs. 5.3.4-10 and 5.3.4-16), the thicker the waste layer the more dominating fermentation becomes. Thus, to the extent that it is desirable to immobilize trace elements within the waste deposit, criteria controlling the maximum thickness of the waste layer may need to be established. Future modeling studies should incorporate metal contents of the waste material to evaluate this aspect.

(2) Formation of Gas Hydrates

Extremely high carbon dioxide and methane concentrations are predicted to occur during the first few hundred years after the waste is deposited. This is especially true at site B where the waste layer is nearly 14 m thick. At abyssal temperatures and pressures, these gas concentrations should be sufficient to drive gas hydrate formation (Sloan 1990). However, numerous aspects of this system may confound attempts to accurately predict clathrate formation. The various factors that must be considered include the temperature of the deposit and the presence of inhibitors.

If gas hydrates form, many of the aspects of the simulations presented must be changed. Most significantly, clathrate formation will reduce the porosity of the deposit, decreasing the diffusive exchange of oxidants and reduced solutes and other dissolved chemical species. Extensive clathrate formation would, therefore, significantly increase the recovery period of the seafloor area and alter predictions of material exchange between the waste layer and the bottom waters and benthic biological community.

(3) Physical Transport and Exchange Processes

For all of the simulations presented here, the transport and exchange rate of solutes has been assumed to be governed by molecular diffusion. In undisturbed abyssal environments, molecular diffusion has been demonstrated to be the dominant solute transport process. The growth of the impacted sediment layer and the eventual recovery of the pore-water system depends specifically upon this assumption. If conditions or processes occur that alter net transport rates, the results of the simulations will be in error. Possible factors that may alter dispersion rates within the sediments include clathrate formation, advective fluid flow, and solid surface solute interactions.

As discussed above, the formation of clathrates within the pore spaces of the waste layer would reduce the porosity and permeability of the deposit. In the extreme, clathrate formation might entirely seal off the waste deposit. In addition, hydrate formation may serve to stabilize the occurrence of methane in the sediments, while in the present simulation, methane is permitted to freely react with sulfate via anaerobic methane oxidation.

Any form of fluid flow would significantly alter the predicted distributions. Flow may occur in response to compaction of the deposit due to a combination of increased overburden and material loss by decomposition or by buoyancy created by warming pore waters through the heat of decomposition. Because of the relatively larger thickness of the waste layer, even very slow advection would have a very dramatic influence on predicted exchange and recovery rates.

Finally, in the present simulation, the solute solid reactions were not considered. Examples of these types of reactions would include the formation of metal sulfides and the adsorption of ammonium onto alumino-silicate surfaces. Such reactions would tend to slow the expansion of the ammonium and sulfide layers and thus decrease the thickness of the impacted pore water predicted by the simulation.

(4) Variations in Pore-Water pH and Trace Metal Mobility

In general, trace metals are poorly leached from solid waste materials at near-neutral (pH = 6–8) solution pHs (Roethel et al. 1991). Within this pH range, the solubilization and mobility of trace elements is minimized. Unlike terrestrial environments which may exhibit lower pH values because of the influence of acidic ground waters or acid rain waters, marine pore waters are nearly always within this near-neutral range (Boudreau 1987, 1991).

Based on the predicted concentrations of titration alkalinity and TIC, the pH of the pore waters for all simulation results were calculated. All of the values were determined to be

between pH 5.9 and 8.0. Thus, despite the very large changes that occur in the titration alkalinity and TIC, the pH remains in the relatively narrow, near-neutral range. The pH values predicted by these simulation calculations suggest that the mobility, and hence availability, to benthic organisms of trace metals is minimized.

(5) Chemolithotrophic Bacterial Biomass Production

In the simulation presented here, the oxidation of the reduced solutes, methane, ammonium, and sulfide is treated as a simple chemical reaction with the production of inorganic products. In nature, numerous bacteria have evolved to utilize the energy of these reactions to produce organic biomass from inorganic carbon. These activities act to produce additional POC in the oxidation zone at the top and the bottom of the waste layer. Future modeling and field studies must examine the influence of this additional source of POC to the overall degradation of the waste layer.

(6) Validation Through Studies of Seafloor Turbidites

Turbidites are seafloor deposits that are formed by the rapid transport of materials from continental margins to the deep sea by down slope density-driven currents. Sediments that comprise the turbidites are generally rich in organic carbon relative to abyssal sediments. Thus, turbidite formation represents a natural process by which relatively thick sedimentary layers, rich in reactive organic matter, are rapidly deposited on the deep seafloor.

Numerous turbidites have been identified in the abyssal North Atlantic. The majority of the uppermost turbidites appear to have been deposited during the last glacial period (more than 12,000 years before present). The initial amount of organic matter and the layer thickness are generally less than the hypothetical waste deposit simulated here. Nevertheless, pore-water studies confirm that the organic remineralization occurring in the turbidite layers continues to influence the distributions of pore-water oxidants. In most cases, oxygen consumption in that layer prevents oxygen from penetrating deeper into the sediments, resulting in an anoxic sediment column below. Thus, these natural deposits confirm the simulation result that the introduction of rich, organic, carbon-rich layers will significantly impact the oxidant distribution in the pore waters for tens of thousands of years.

(7) Future Efforts

The above discussion has identified numerous aspects where the present simulation can be improved. Some of these, such as examining metal-sulfide ratios and assessing ammonium adsorption on dispersion rates may be examined through future modeling activities. Others, such as the formation of clathrates and pore-water advection, are too difficult to predict to meaningfully parameterize for numerical simulation. These aspects must be examined directly through pilot field and laboratory projects.

5.3.5 Potential for Formation of Methane Hydrate Clathrate Within Waste Deposited on the Abyssal Seafloor *by Kathleen M. Fischer and Mary M. Rowe*

Geologically, sewage sludge and dredged material deposited on the abyssal seafloor can be considered equivalent to fine-grained, rapidly deposited sediment having unusually high organic carbon content. By virtue of the high organic carbon concentrations, this waste material has the potential to generate significant quantities of methane both prior to and after emplacement on the ocean floor; this potential is limited by the quantities of various oxidants available which, via bacterially mediated reactions, convert organic carbon to carbon dioxide rather than to methane. The conditions at the proposed locations for emplacement of the waste, i.e., water depths in excess of 3000 m and bottom water temperatures of ~2°C, fall well within the range of temperatures and pressures over which methane hydrate is stable (Fig. 5.3.5-1). The question arises whether methane concentrations within the waste will reach hydrate-forming levels.

Methane hydrate is a form of water ice in which high concentrations of methane molecules are physically trapped within a water lattice. Low temperatures, high pressures, water, and concentrations of methane many times in excess of saturation are required for methane hydrate to form. In the Gulf of Mexico, hydrate has been observed at shallower depths and higher temperatures than anticipated by Figure 5.3.5-1 as a result of the presence of minor concentrations of gases such as ethane that broaden the stability envelope. (The byproducts of the decomposition of sewage and dredged materials may have a similar effect.) Methane hydrate contains methane and water at molar ratios ranging from 1:19 (minimum amount of methane necessary for the water lattice to form) to 1:5.75 (each cage in the water lattice is filled with a methane molecule). For example, at 2°C and 30 MPa (conditions similar to ~3000 m water depth in the deep sea), the concentration of methane required to form hydrate is ~50 times greater than the solubility of methane in seawater at this temperature and pressure (Claypool and Kaplan 1974). The mechanism by which methane, in quantities sufficient to form hydrate, is able to concentrate in a region of the sediment column is not understood at this time, but generally it is assumed that a large portion of the methane found in naturally occurring hydrates has migrated from deeper in the sediment column. Methane hydrate has been found in continental margin sediments at various depths from the seafloor to ~550 m subbottom, depending on the thickness of the overlying water column and sediments (pressure) and the geothermal gradient (temperature).

Hydrate formation within the deposited material will affect several physical properties of the waste material by increasing the rigidity, infilling pore space with hydrate (and thereby possibly decreasing the permeability and the bulk sediment diffusion coefficient), and decreasing specific gravity. The hydrate will persist within the material as long as temperature and pressure conditions remain within the hydrate stability region. One of the most important concerns is the potential change in bulk specific gravity of the deposited waste. The presence of hydrate within the waste deposit will increase the buoyancy of the material, thereby increasing the potential for redistribution. In addition, if the hydrate-bearing material moves upward in the water column and out of the hydrate stability region, the hydrate will decompose. Potentially significant concentrations of methane may be released into the ocean and possibly the atmosphere as well.

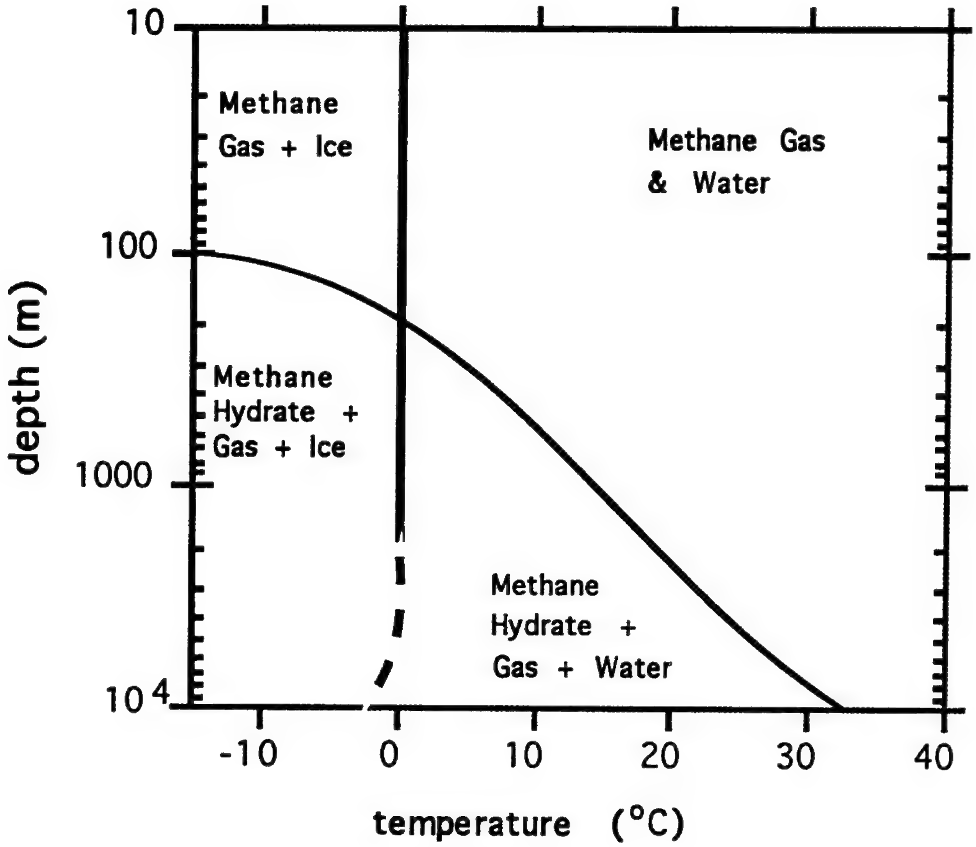


Fig. 5.3.5-1. Phase boundary diagram for the system containing methane, as the gas or hydrate, and water, as liquid water or ice. Redrawn from Kvenvolden and Barnard (1982).

Whether methane hydrate will form in the deposited waste largely depends upon whether there is sufficient methane available. Figure 5.3.5-2 is a plot of organic carbon content versus percent conversion of organic carbon to methane for sewage sludge containing 20% solids. The line through circular data points represents the 1:19 molar ratio of methane to water, which is the minimum necessary to form hydrate. To the right of this line, the 1:19 ratio has been exceeded, and sufficient methane is present to form methane hydrate. When methane:water ratios exceed 1:5.75, excess methane is present as free gas. For wastes with higher percent solids concentrations, these lines shift to the left, i.e., either lower organic carbon content or lower percent conversion is sufficient to produce the minimum 1:19 ratio of methane to water. Inherent in this analysis is the assumption that all methane is generated in situ, i.e., within the waste material without contributions from deeper in the sediment column. Issues such as diffusion or ebullition of methane from the waste, presence or influx of oxidants, presence of appropriate bacterial species, and rates of methane hydrate formation have not been considered in this simple analysis.

Although methane hydrate formation in offshore gas/oil pipelines has been studied in some detail, there are many unique issues to be addressed to assess the potential for methane hydrate formation within waste deposited on the abyssal seafloor. The limiting factor for methane hydrate formation in the abyssal seafloor environment is the attainment of concentrations of methane necessary for hydrate to form. Waste material that is bagged may generate methane even before it is deposited on the seafloor via the activity of endemic bacteria if oxidants, e.g. oxygen, nitrate, and bacterially reducible metal oxides, are no longer available. Thus, deep within the waste pile, methane generated prior to emplacement may be trapped, forming hydrate when the material reaches the abyssal seafloor.

Methane is generated as a byproduct of bacterial activity. Depending on the source of the waste, endemic bacteria may be species that normally live over a narrow range of salinities and at approximately one atmosphere pressure and ~20°C. Certain bacterial species may be incapable of surviving the transition to the low temperature, high pressure, saline conditions of the abyssal seafloor. In the event of complete mortality of the endemic bacteria, emplacement of waste in the new environment means that marine methanogens must colonize the waste for methane generation to resume. All methanogens (methane-producing bacteria) require anoxic conditions to convert organic carbon to methane. Other bacteria can, in the presence of oxidants, convert methane to carbon dioxide. If methane is generated at a faster rate than it can escape to bottom waters or be consumed by oxidation, methane concentrations may build to hydrate-forming levels within the waste. This will depend on the escape rate of methane, via diffusion of dissolved gas or percolation of bubbles, through the waste and bag material (if present). Additionally, diffusion rates of oxidants, particularly oxygen, into the waste and methane oxidation rates will determine the concentration of methane within the waste. If the waste material is not contained, or if the enclosing bag ruptures, the permeability of the bag material is no longer an issue, and methane will more easily escape into the surrounding environment as it is generated. However, fine-grained sediment deposited at a rapid rate, i.e., similar to the disposed waste, is known to trap pore fluid and gas to a greater extent than coarser-grained sediment or sediment deposited at a slower rate. Depending on the properties of the waste material, the methane generated deep within the deposited material may be trapped and form methane hydrate.

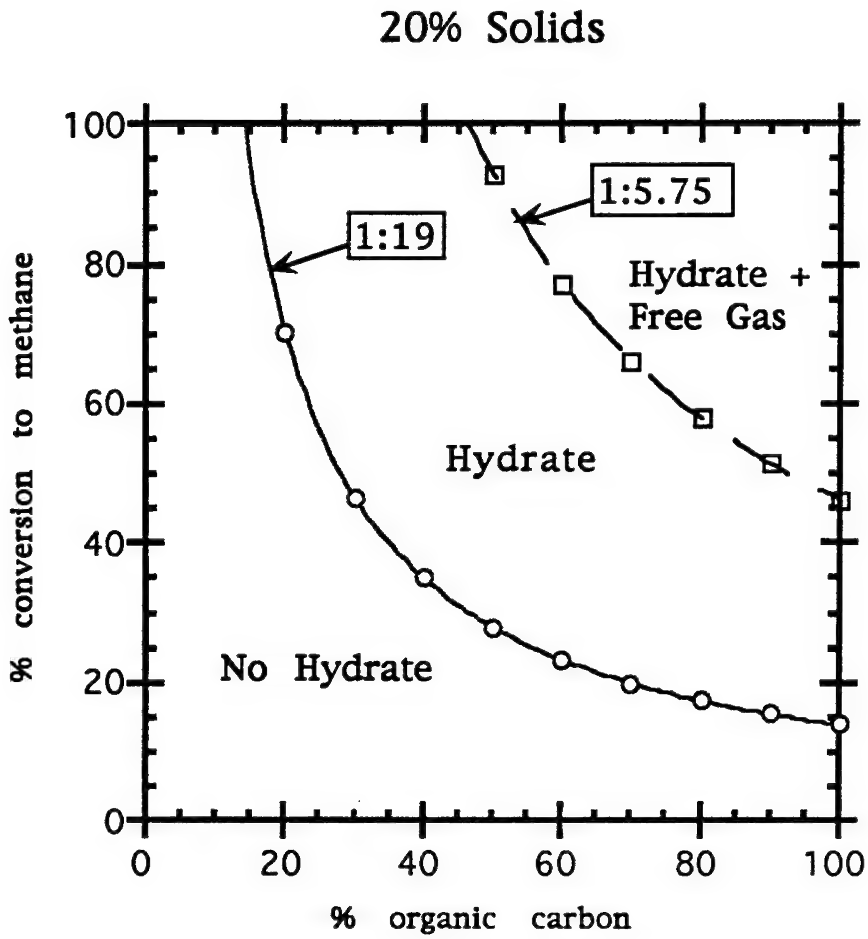


Fig. 5.3.5-2. The following equations were used to produce the curves:

$$\frac{(\%C_o)(\%C_v)(\%S)(18)}{(10^4)(100\text{-}\%S)(12)} = \frac{1}{19}$$

$$\frac{(\%C_o)(\%C_v)(\%S)(18)}{(10^4)(100\text{-}\%S)(12)} = \frac{1}{5.75}$$

where $\%C_o$ is percent organic carbon, $\%C_v$ is percent conversion of organic carbon to methane, and %S is percent solids.

5.4 Ecology

5.4.1 Numerical Simulations of Deep-Sea Food Chains with an Estimate of Potential Export of Contaminants from Abyssal Waste Isolation Sites

by Gilbert T. Rowe

5.4.1.1 Fluxes in Deep-Ocean Ecosystem Food Chains

A generic "flux" diagram (derived in principle from Eugene Odum and his students, esp. John Teal's (1962) salt marsh paper) provides a set of criteria for describing benthic ecosystems in terms of flux of organic matter and remineralization of metabolic byproducts (Fig. 5.4.1-1). The particular system at a waste isolation site at abyssal depths will probably undergo a change from the extreme "oligotrophic" case (food-starved) to the extreme "hypertrophic" case (carbon-rich). A basic principle in this characterization is that the system can slide back and forth between these extremes. The "shift" is a function of organic matter inputs and oxygen supplies. In the following modeling exercises, we are pursuing the hypothesis that the oligotrophic benthic case characteristic of the abyssal seafloor will move toward the hypertrophic case when inundated with organic-rich material. Once inundated, the biotic assemblage species composition will change as described in Section 5.4.2, **Effects on Benthic Ecosystems by Disposal of Wastes on the Deep-Seafloor**.

The following numerical simulation exercises do not address species composition, but rather biomass of functional groups and the cycling of matter. The models attempt to simulate how the distribution of biomass is altered by the new source of organic matter. Ultimately, the intent of these simulations is to demonstrate how the living biomass might "export" contaminated materials out of the deep sea into surface water or into living resources to which man might be exposed. The numerical experiments adhere to the principle that contaminants will be dependent on the living components of the food chain, as represented by the carbon cycle (Rowe et al. 1986), for biological transfers within the chain and ultimately out of the immediate seafloor environment. In the present case, it is assumed that lecithotrophic (yolk-containing) larvae float to the surface. As formulated here, these models do not include physical dispersal of contaminants from the site, only the potential for biological export.

5.4.1.2 Time-Dependent Numerical Model

We created a running numerical simulation of the basic elements of a deep-sea food chain using a simulation software package called STELLA II. It is available for Macintosh computers from High Performance Systems, Inc., 45 Lyme Road, Suite 300, Hanover, NH, 03755. Similar simulations can be run on an IBM PC with Dynamo Plus simulation system, available from Pugh-Roberts Associates, 41 William Linsky Way, Cambridge, MA, 02142. STELLA allows the user to draw an ecosystem as boxes (for state variables or concentrations) and arrows (for fluxes). To each drawing, arrows are added that stipulate how the dynamics of each flux is to be controlled in time, based on the known relationships between the boxes and empirical constants. After a set of initial conditions is entered by the user, he can then run the simulation for a desired time. The package automatically writes the differential equations necessary to simulate the system based on the drawing. The system

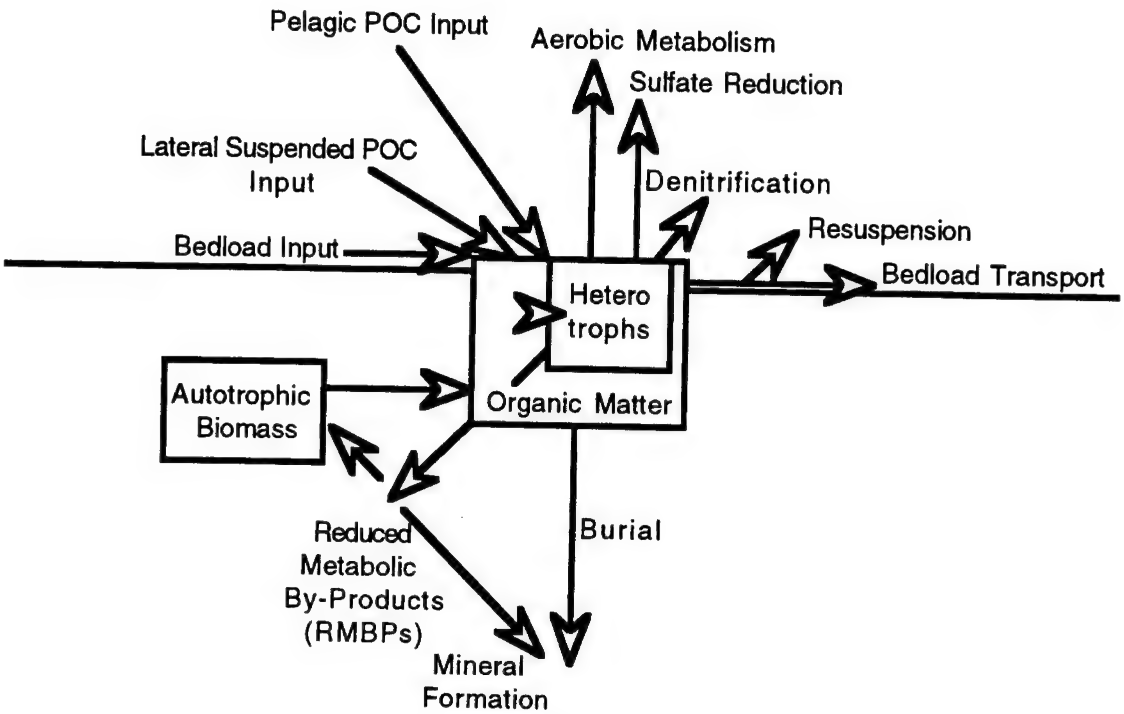


Figure 5.4.1-1. Generic flux diagram for benthic community and associated geochemical processes. Inputs of organic matter enter the system on the left; the products of remineralization leave the system on the right. Autotrophic processes take carbon dioxide and resynthesize organic matter from it within the system. Burial results from mineral formation or accumulation. The sizes of the fluxes into the system on the left control the relative sizes of the arrows exiting on the right. No biological export is included in this model. These would be gonad products leaving the system, predation, migration or fishing. The following simulations include "eggs" as an export term.

of equations is solved numerically using traditional Euler solutions, but time steps can be changed and other numerical approaches (e.g., Runge Kutta) can be selected as necessary.

5.4.1.3 Model of the Natural System

As a basis for our model experiments, we utilize published data for the Surrogate Site Pacific-2 at a depth of ca. 5.8 km (Smith, K. 1992). The units used are mg C per m^2, with fluxes in the same units but with time in days. (These differ from those published by Smith, who used grams carbon per km^2-day.) The model has been simplified a little from Ken Smith's original, based on the data available. While we can equate six stocks with those defined by Smith, our model, as a simplified heuristic example of this process, has only three state variables or standing stocks; we lumped all the sediment biota and left out all the water column biota, except for the megafauna living on the sediments, which was our target group. The biomass of the biota in the sediments was the sum of Smith's values (for microbiota (=bacteria principally), meiofauna and macrofauna), and the megafauna value was directly from Smith; it included no fishes or carcasses. Instead of looking at the top 55 mm of sediment as he did, we reduced the depth covered to the top 5 mm: that is, the values for the sediment carbon were reduced by a factor of 10. However, we did not reduce the biomass of the sediment biota; we utilized directly what Smith reported on a per-square-meter basis, and made the assumption that they all feed for the most part in the top 5 mm.

First we solved for steady state. This required calculating an input term to make the system reach steady state. Smith, in earlier work (1987), had pointed out that the input measured in sediment traps did not match the summed utilization based on oxygen demand for the various components of the system. This could be due to lateral input, as suggested by Jahnke et al. (1990), failure to measure pulses of organic matter (Smith et al. 1992), lack of steady state within the system, or experimental error. In the model, the needed influx was added in several ways: first as a zero-order constant flux in original simulations and later as a time-dependent pulse occurring over one season of the year. It might be noted that in the western North Atlantic the opposite has been observed; the input to sediment traps is greater than the sediment oxygen demand (Rowe and Gardner 1979; Anderson et al. 1994).

First we ran a two-box or compartment system consisting of "organic matter" and "heterotrophs" with a constant input of POC (rain of particles). After finding steady state for that situation, we added a seasonal cycle that mimics the general pattern from numerous sediment trap deployments (Deuser et al. 1981) including the North Pacific (Smith et al. 1992). Then we added "megafauna" (Fig. 5.4.1-2, box model) and fed them with the growth of the "heterotrophs." Growth in the heterotroph component was accomplished by setting the feeding rate a little bit larger than the respiration (e.g., the first-order growth constant was slightly larger than the first-order respiration rate constant). The feeding rate of the "megafauna" was parameterized as a second-order function of biomass of the donor (heterotroph) and recipient (megafauna) stocks. The transfer constant used was determined from Smith's original data. As our goal for this "natural system" was to estimate export from the larger organisms, we let the megafauna produce eggs which would be released continuously over the course of a year. This was set at 0.05, or a constant fraction of the

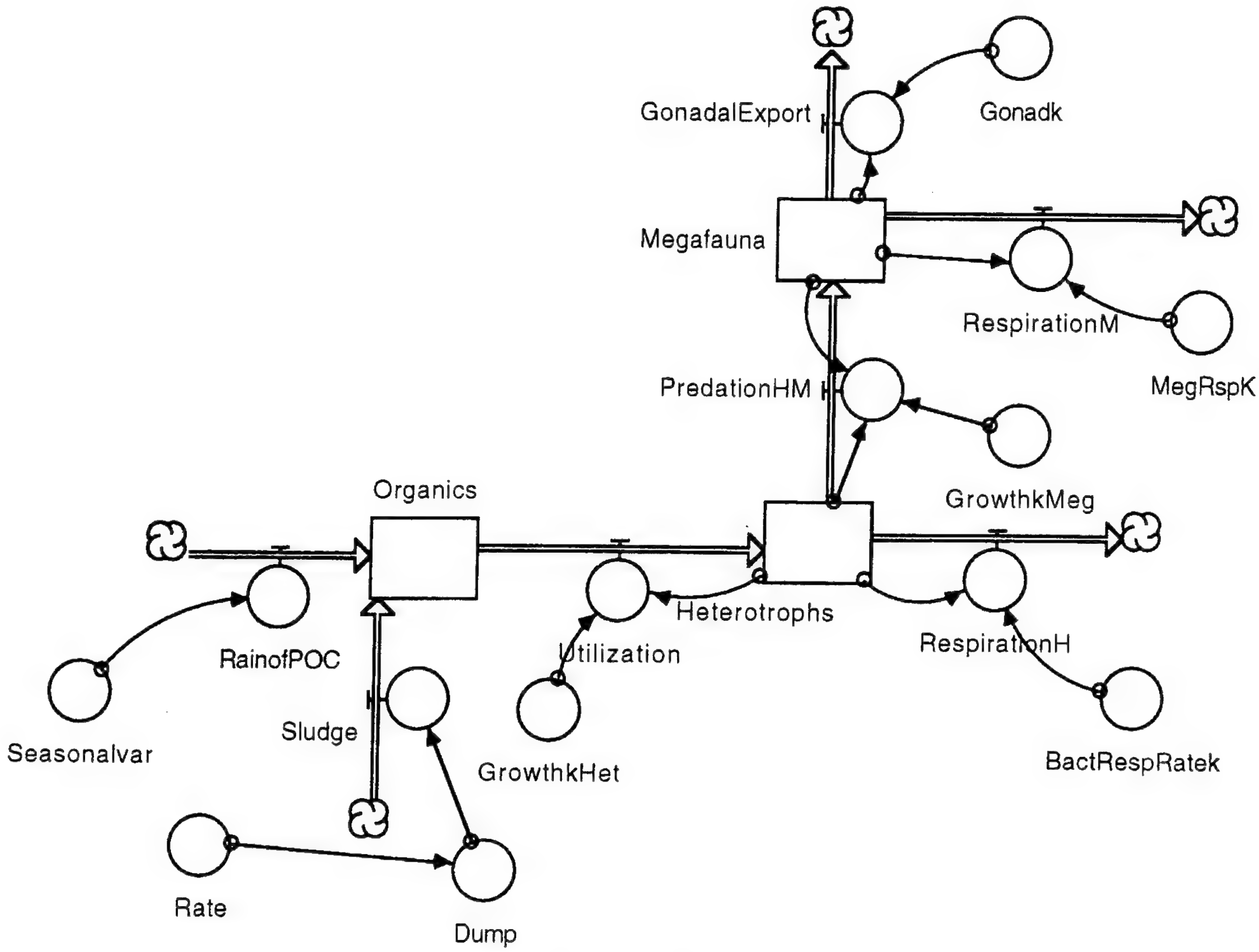


Figure 5.4.1-2. Conceptual model of a 3 compartment deep-sea food chain (based on paper by Smith (1992), in a study of the deep North Pacific, but with some compartments combined (see text)). This formulation is used as the basis for numerical simulation of fluxes and stocks over time, based on Smith's conditions (the initial conditions used) and incorporating transfer coefficients derived from Smith's data.

megafauna biomass. Ultimately, we let this three-box model run for 10 years; steady state was achieved in about two to three years, as illustrated (Fig. 5.4.1-3, simulation), for the natural system.

Note that the steady-state living stocks and fluxes vary with time, but that these variations were not unreasonable; they are within the statistical ranges for the values presented by Smith et al. (1992). The principal disparity was between sediment detrital carbon stock size as measured by Smith and the steady-state value we ended up with. The carbon in the sediments was measured as total organic carbon, which may be the cause for the inconsistency. Much of the organic detrital matter cannot be characterized chemically and is assumed to be relatively unreactive with little biological value as a source of food for detritus-consuming organisms. That we achieved steady state with first-order equations, with no maxima on rates to prevent explosions and crashes, implies that our qualitative and quantitative understanding of the natural system is reasonable.

The assumed exported products in this simulation are eggs or larvae. This has been defined as a constant fraction of the megafauna biomass, which were assumed to release reproductive products constantly, albeit at a low rate (see Gage and Tyler 1991, pp. 300–335). This export declined with time, as the resource (the original sediment detrital carbon, presumably) was slowly depleted. Integrating under this line, which we did graphically, provided an estimate of 209 mg C m^{-2} for the amount of exported gonadal products over the 10-year period in question, which is equivalent to 57 μg C m^{-2} day^{-1}.

5.4.1.4 Sludge Emplacing Model

The next set of numerical experiments deals with actual sewage sludge emplacement. The three-box diagram has been retained, but with an added input into the bottom sediment organic matter stock (Fig. 5.4.1-2). For our initial input data we turned to studies of sewage sludge disposal from Los Angeles into the deep basins off southern California (Jackson et al. 1979). In that study, they estimated that input of solids over the basins in question would equal or exceed natural inputs (26 mg cm^{-2} $year^{-1}$), and that the biological oxygen demand (BOD) would equal or exceed natural BOD (10^4 moles-O_2 km^{-2} day^{-1}). Given that the area involved was ca. 120 km^2, the BOD would oxidize on the order of 120 mg C m^{-2} day^{-1}(units in the model). If the input of solids is assumed to be 50% organic matter (e.g., 25% organic carbon), this would equate to 164 mg C $m^{-2}day^{-1}$, again using the model's units. Initially we used 100 mg C m^{-2} day^{-1} for the first dumping experiment. This input on a per-day basis is about 10 to 100 times that recorded for the deep-sea sites in question, but it is about equal to rates on a typical continental shelf environment (Rowe et al. 1988). It is well below that expected for a "hypertrophic" or overloaded system.

For a single year, with the input term increased to 100 mg C m^{-2} day^{-1}, the model produced two peaks of gonadal export approaching 1 mg m^{-2} day^{-1}, over the 10-year simulation (Fig. 5.4.1-4). Next, the year-long pulse was increased in intensity to 1000 mg C m^{-2} day^{-1}. Such a rate would approximate the highest values for inputs of organic carbon of which we are aware in nature, e.g., intense upwelling systems, estuaries, the Mississippi River delta region, etc. In this case, as a result of the ways in which the whole food chain

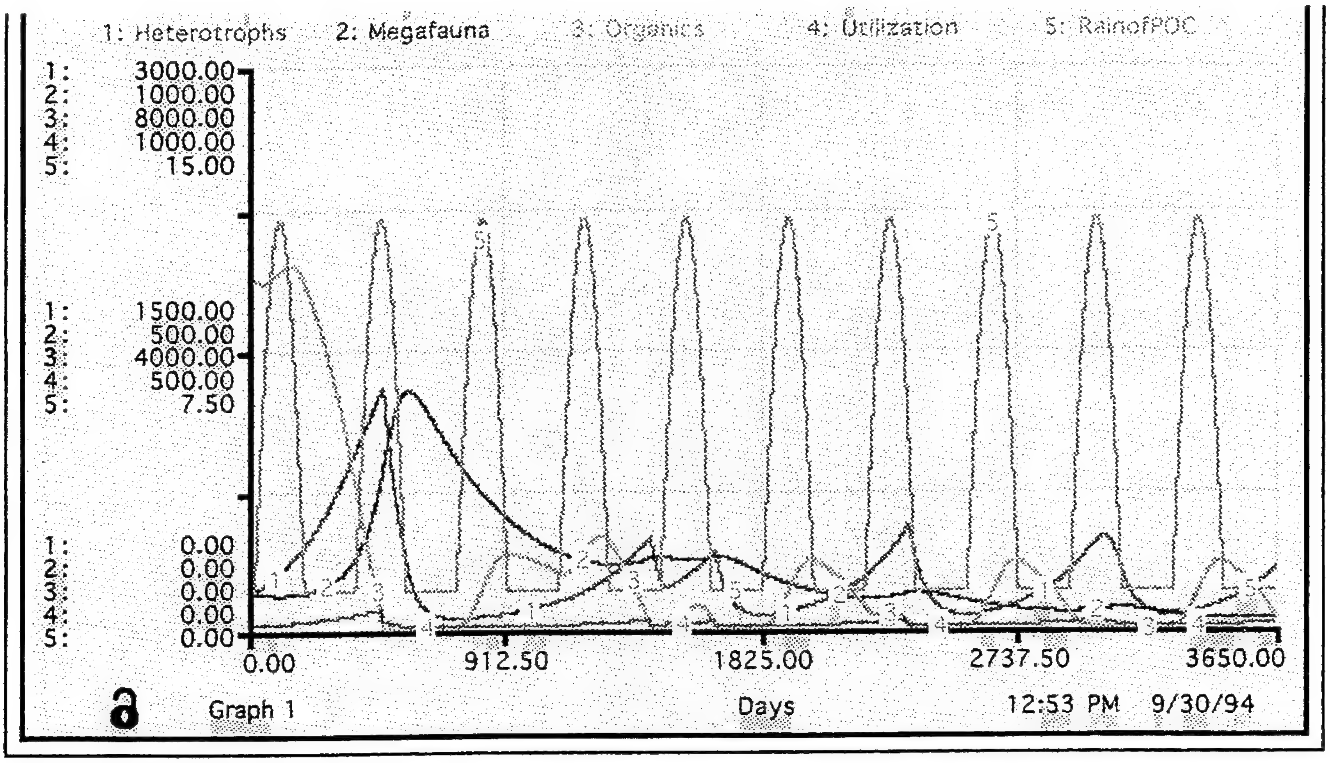


Figure 5.4.1-3. Output of numerical simulation of deep-sea food chain model. In this case, the input of sludge was zero. Units are in mg C m^{-2} or mg C m^{-2} d^{-1}.

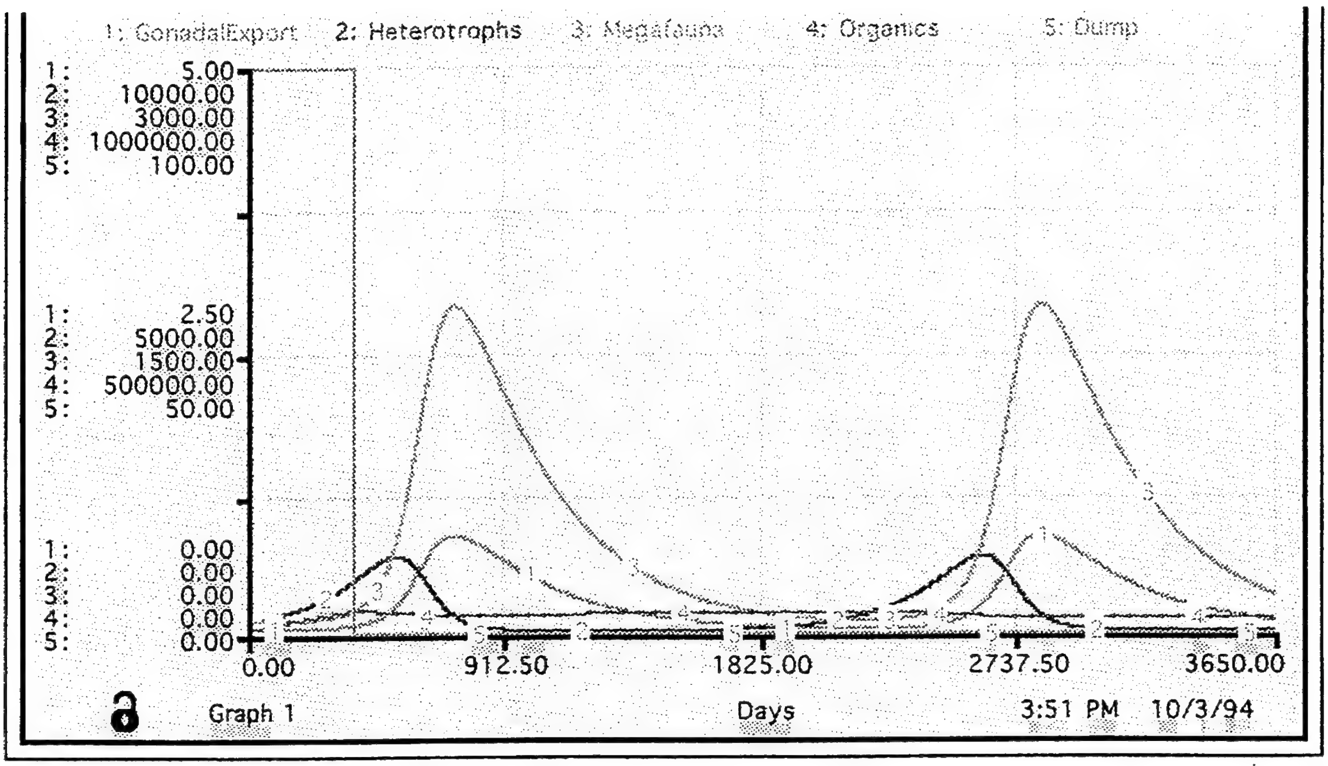


Figure 5.4.1-4. Output of numerical simulation as in Figure 5.4.1-3, but with sludge input for one year equivalent to that expected (ca. 100 mg C m^{-2} d^{-1}) for the basins adjacent to Los Angeles (from Jackson et al. 1979).

system was parameterized, the export was no different (Fig. 5.4.1-5) from that at the lower rate of 100 mg C m^{-2} day^{-1}.

Once the input of organics had occurred, the rates of processes by the biota set an upper limit on the impact that the heterotrophs had on the new organic material. To some degree these rates were set by the constants derived from Smith's original data; they represent deep-sea organisms adapted to a situation in which the natural input of organics is very low. If the utilization rates per unit biomass were to increase to mimic shallow-water species, then the overall rates at which the sludge was remineralized would increase proportionately. Unfortunately, at this time we do not know if such changes in deep-sea biota will occur. Secondly, the limitation on the overall rates of utilization within the 10-year model run were a result of a self-limitation imposed by the structure of the food chain. The predators (megafauna) overate their prey (heterotrophs) down to a threshold value (set by the model builder). After the heterotrophs were in essence wiped out, the megafauna crashed because they had too little to eat. What has been observed in these models are cycles that are typical of predator-prey or Lotka-Volterra relationships. There is a possibility that this was realistic; many such cycles are observed in both terrestrial and aquatic ecosystems. However, it is also possible that this was an artifact of the oversimplication of the food chain itself.

5.4.1.5 Coupling the Sludge Carbon Cycle to Contaminant Export

If we had units of polycyclic aromatic hydrocarbon (PAH) concentration on the basis of ppm per unit weight of carbon, then the export of PAHs per year would be the integral of the export curve over the year (Fig. 5.4.1-6) times the concentration of PAH times the area of the site:

$$\text{PAH export/year} = \text{gonad export} \times [\text{PAH}] \text{ in gonad} \times 365 \text{ days per year} \times \text{area of the dump site}$$

This reproduction is over a year; if they reproduce in a week with the same intensity by storing eggs up until their designated week (Gage and Tyler 1991), then the flux concentrated into 1 week would be 52 times the value scattered over the year. But then they would be finished and have to store up for another year.

Sludge dumped at Site 106 southeast of New Jersey has a PAH concentration of 1.4 mg g-dry wt^{-1} (O'Connor et al. 1983). If we assume that 50% of the sludge dry weight was organic matter and 50% of the organic matter was carbon, then the sludge would have had a concentration of 5.6 mg PAH per gram carbon. If we assume that the concentration of PAH in eggs and larvae was the same as that in the sludge, and the integrated export of carbon over a 10-year period (from the model calculations) was ca. 1.0 g m^{-2}, then the export of PAH would have been 5.6 mg m^{-2} – 10 $years^{-1}$. If a hypothetical circular dump site had a radius of 1 km, then the area of the site would be 3.14 km^2, or 3.14×10^6 m^2. The total site export of PAH under such circumstances, based on the model's calculations, would be on the order of 1.7×10^7 mg PAH over a 10-year period (1.7 g PAH $year^{-1}$).

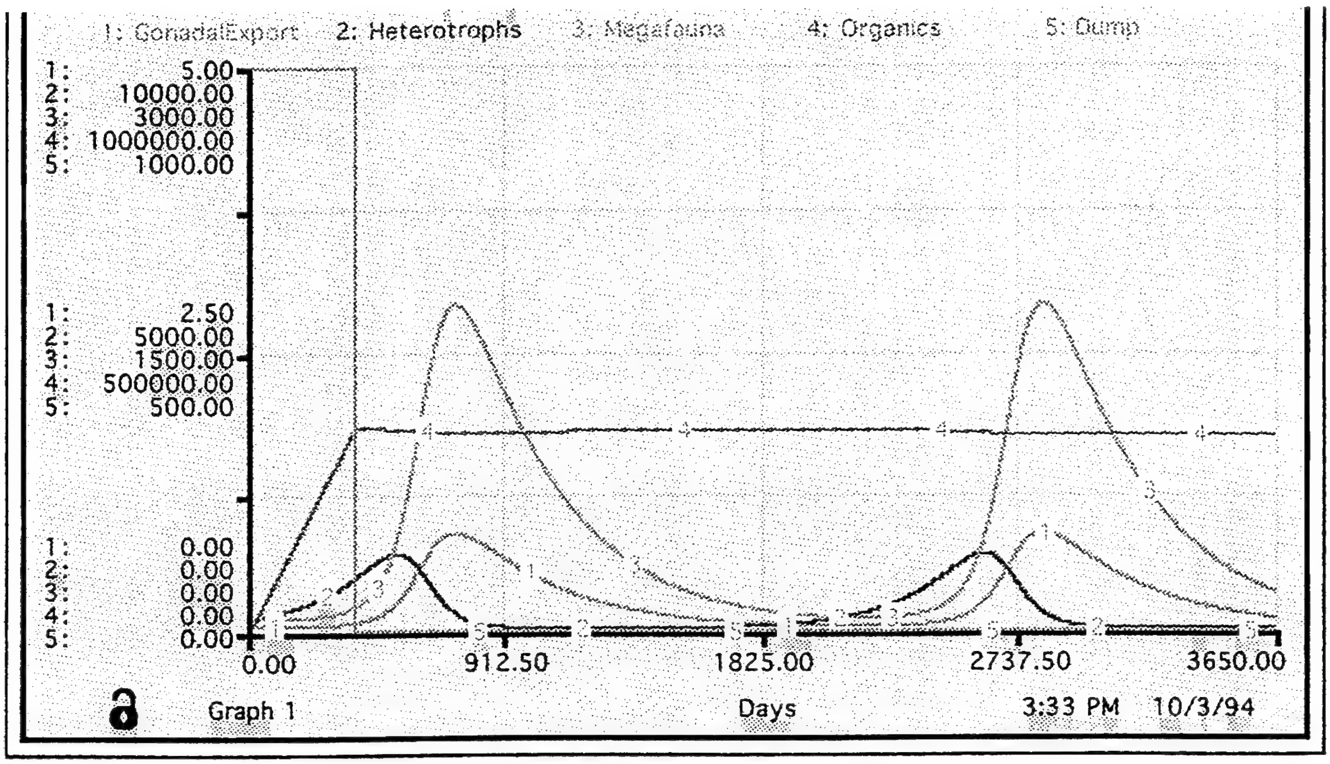


Figure 5.4.1-5. Output of numerical simulation as in Figures 5.4.1-3 and 5.4.1-4, but with sludge input of 1000 mg C m^{-2} d^{-1}).

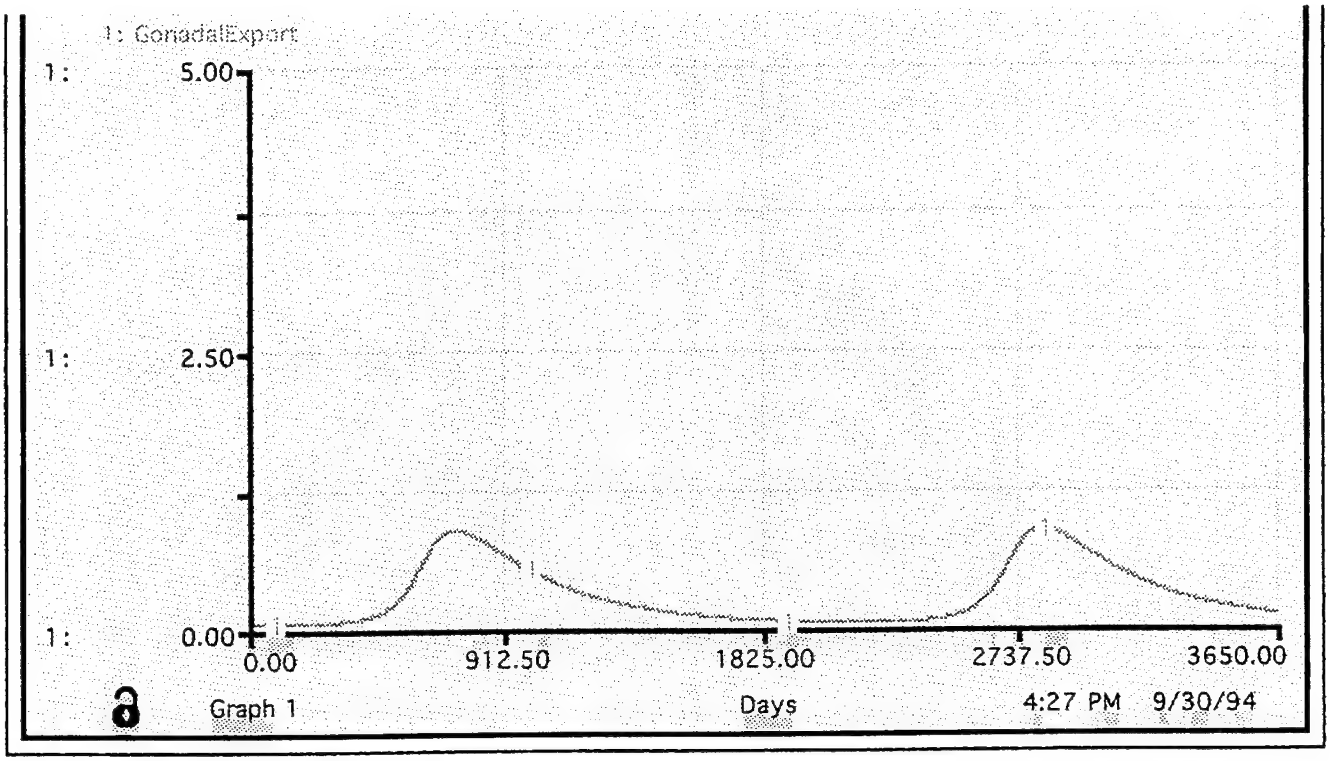


Figure 5.4.1-6. Output of numerical simulation illustrating two peaks of "gonad export" products over a 10-year simulation.

The above interpretation of the food chain at a hypothetical dump site assumes that a resident megafauna grows in response to the growth of its presumed prey, a group of smaller invertebrates and bacteria referred to as heterotrophs. It is from this growth or increase in megafauna biomass that the increase in export occurs in response to the dumped sludge. The model does not differentiate between recruitment of new larvae or juveniles from reproduction and growth of species already in the area of the site. In terms of the growth response of the megafauna, this may not make any difference to the final outcome; increases in predator biomass will depend on increases in prey biomass. Another type of increase in predator biomass would be a chemotactic attraction in response to something in the dumped material. It is well documented that widely ranging scavengers such as rattail fishes and relatively large crustaceans (Amphipoda) are almost immediately attracted to carcasses anchored to the seafloor. Whether such attraction to sewage sludge occurs remains to be tested. Any future modeling efforts should incorporate this phenomenon.

5.4.2 Effects on Benthic Ecosystems by Emplacement of Wastes on the Abyssal Seafloor: Spatial and Temporal Scales *by David K. Young*

5.4.2.1 Introduction

From an ecological viewpoint, the deep sea can be viewed as the ultimate sink for all wastes resulting from human activities on Earth. Deliberate disposal of significant quantities of wastes in the oceans has occurred and is presently practiced at continental slope depths and shallower, with several exceptions, as reviewed in the section on **Past Studies** (this report). Most anthropogenic wastes, which have been found on the deep seafloor, result from materials dumped from ships ever since humans started crossing the oceans. Because of the vastness of the abyssal ocean relative to amounts of material, this shipboard waste has not had a deleterious effect on deep-sea benthic fauna (Gage and Tyler 1991). Thus, effects of wastes on the deep-sea benthic fauna, or so-called benthos, cannot be predicted from direct experience or observations because waste disposal has not occurred on the scale it has in shallow seas and continental margins. It is well documented (reviewed by Gage and Tyler 1991) that many species are unique to the deep sea and that they have been physiologically adapted to this environment over geologic time. It is not known, however, to what degree of reliability that analogies to abyssal life forms can be drawn from certain of their better-known shallow-water counterparts with regard to their ecological requirements (Jumars and Gallagher 1982). It is even less well known what would be the responses of deep-sea benthos to disposal of wastes in quantities that have been experienced by shallow-water marine benthic fauna. The wastes for which environmental impacts are best known are dredged materials and sewage sludge; accordingly, only those components (see Section 1.3, **Waste Stream Analysis**) will be considered here.

In spite of the foregoing uncertainties and limitations, it is useful to examine what may be extrapolated to the abyssal ocean from shallow-water examples and to determine what generalizations may apply to the assessment of potential effects on benthic ecosystems by disposal of wastes on the deep seafloor. In this approach, we abandon the view of benthic fauna as only taxonomic (i.e., species, genus, etc.) entities and adopt the viewpoint of them as functional groups in terms of their type of feeding (i.e., suspension, deposit, carnivore,

or scavenger), motility (i.e., sessile or mobile), and "Lebensspuren" (i.e., life traces). These functional groupings include the view of an assemblage of interacting organisms, as a benthic community, affecting and affected by the environment and effecting changes to that ecosystem. Because photoautotrophic organisms are not found at abyssal depths, we restrict our considerations only to chemoautotrophic and heterotrophic components of benthic ecosystems. We also restrict our study to low-energy regimes of the abyssal seafloor which are suitable for waste isolation.

5.4.2.2 Shallow-Water Marine Benthic Ecosystems

The initial effect of sudden deposition of significant quantities of dredged material and sewage sludge on the shallow seafloor is to cover the existing sediment surface and to bury the benthic fauna. Depending upon the depth of burial, usually only those individuals of the benthic community that survive are the ones able to reposition themselves at the new sediment-water interface, i.e., the mobile forms. If the amounts of waste material are sufficiently thick, the entire benthic community may be wiped out and recolonization of the new sediment surface takes place from adjacent populations. Assuming that the waste materials are not toxic to recruiting larvae, juveniles, or motile adults, the new deposit is subjected to biogenic reworking, i.e., bioturbation, and is thereby changed in terms of its physical properties and attendant geochemical processes occurring within the sediment. The functional group of the benthic community primarily responsible for bioturbation activities are the deposit feeders, i.e., the sediment-ingesters. The spatial and temporal scales of successionary changes resulting from waste deposition have been measured for shallow-water marine ecosystems (Pearson and Rosenberg 1978; Rhoads et al. 1978), but the scales on which these changes occur is not known for the deep sea.

5.4.2.3 Deep-Sea Benthic Ecosystems

The benthic fauna of abyssal seafloor sediments are characterized by sparse and small deposit-feeding individuals having a low aggregate biomass which is a result of extremely low fluxes of organic matter reaching these great depths of the deep sea (reviewed by Rowe 1983). The spatial scales of feeding and interactions among these individual animals have been characterized as 0.01 m^2 or smaller (Jumars 1976). Biases in sampling methods toward the macrobenthos (usually defined operationally as those organisms retained on sieves with mesh sizes of 0.3–1.0 mm) have probably underestimated the large, foraging, and scavenging animals (i.e., demersal fauna) that swim just above the bottom and may comprise an important component of the total biomass of deep-sea fauna (Jumars 1993). Although represented by low densities in abyssal plains, certain large invertebrates (mostly represented by the dominant holothurians and asteroids) feed selectively on surface sediments (Briggs 1985) and leave characteristic Lebensspuren, generally smoothing out seafloor relief, in their motile deposit-feeding activities (Young et al. 1985). Deep-burrowing fauna, known primarily by their Lebensspuren (e.g., mounds, pits, and burrows), are acknowledged to be undersampled in deep-sea sediments (Jumars 1993).

Perhaps the best analogy in the deep sea to a sudden deposition of dredged material or sewage sludge to the shallow-water marine seafloor is the episodic depositional event caused by turbidity flows (for description of this phenomenon, see Section 5.2.2, **Sedimentary Regimes.** Jumars and Wheatcroft (1989) examined turbidite sediments as important sources of organic enrichment to deep-sea fauna but noted that the successionary sequences and time of recovery from the initial disturbance are unknown. Seasonal increases in bioturbation rates have been measured in response to phytodetrital depositions (Smith, C. 1992) and initial recolonization by benthic macrofauna has been shown to occur within 6 weeks of small-scale (0.01–1.0 m^2) experimental disturbances (Smith 1986). It has been shown in other small-scale experiments (Grassle 1977) that it takes several years for small, opportunistic benthic species to begin to colonize defaunated deep-sea sediments. After five years, trays of azoic sediment did not achieve the densities or species composition of the benthic community in the surrounding North Atlantic abyssal sediments (Grassle and Morse-Porteous 1987). The different time scales for benthic colonization from weeks (Smith 1986) to years (Grassle 1977) is probably due to differences in experimental design in which colonization of azoic sediment in trays was limited to planktonic larvae (Grassle and Morse-Porteous 1987). There are many problems in "scaling up" such small-scale observations and measurements to turbidity flows (with areas of 10^2 to 10^4 km^2) that occurred thousands of years ago, but it is useful for understanding the ranges of spatially and temporally scaled responses of benthic communities to organic enrichment and disturbance.

Evidence from hadal depths (7000–7500 m) of the Aleutian Trench (Jumars and Hessler 1976) shows that sedimentation of organically rich terrigenous materials over scales of geologic time may result in unexpectedly high abundances and biomass of benthic fauna. The seafloor of the Cascadia Channel (off the Pacific northeast U.S. coast), having received numerous turbidity flows of Pleistocene age, has four times more abundant benthic fauna than that of the adjacent Cascadia Abyssal Plain (Griggs et al. 1969). More recent turbidity flows of sediment with low amounts of organic matter may have the opposite effect, however, as shown in the Puerto Rico Trench (Richardson et al. 1994) by depressing benthic faunal abundances and biomass. Observations from benthic sampling of a recent turbidity flow off the west coast of Africa showed sediments devoid of benthic fauna after several years (Angel 1994).

Episodic Deposition Scenario: By examining published evidence from a turbidite sedimentary province in which the sediments, benthic fauna, and depositional rates have been studied, one may gain some understanding of the spatial and temporal scales of change and recovery of a deep-sea benthic ecosystem from the impact of an episodic deposition of material in abyssal depths. We choose a well-studied turbidite site (reported in a compilation of papers in Young and Richardson 1985) at 5010 m water depth in the central Venezuela Abyssal Plain to analyze the spatial and temporal effects of such a scenario. This approach may be viewed as a "natural experiment" in that a natural phenomenon has provided an opportunity to study effects from an episodic event of such a large spatial and temporal scale that would be difficult to reproduce in a controlled experiment.

The turbidite site in the central Venezuela Abyssal Plain is located (13°45′N; 67°45′W) at the distal end of a ponded turbidity flow originating from the Magdalena Fan carrying organically rich (up to 1.55% organic carbon) terrestrial materials to an organically poor

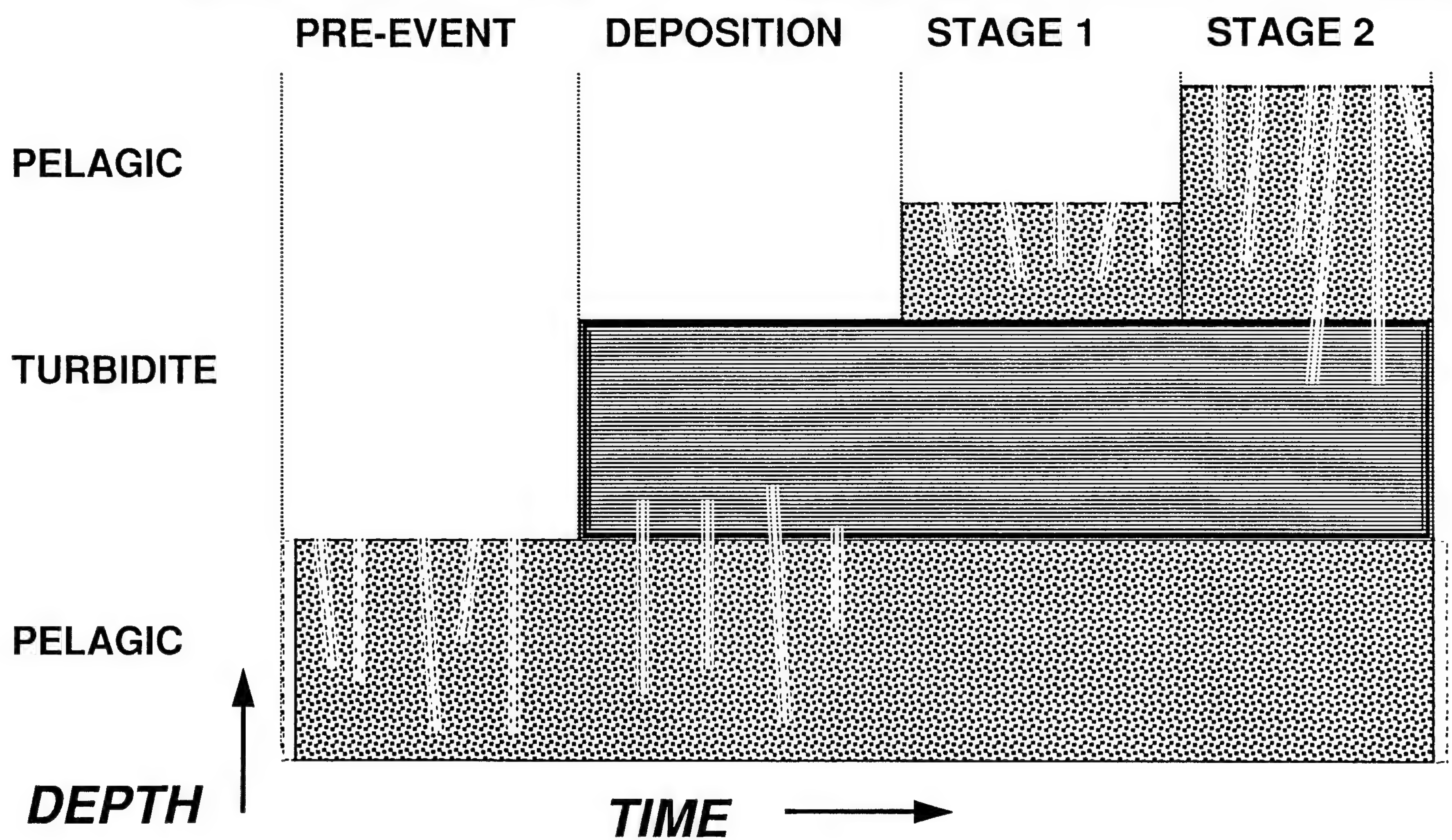
(<0.4% organic carbon) pelagic sedimentary regime. The scenario, as evidenced by the episodic deposition of sediment at the turbidite site, is depicted in Figure 5.4.2-1. We suggest that this scenario would be similar (except in scale) to an event in which one deposits large amounts of material, rich in organic material of terrestrial origin, from a coastal dredging location to a central abyssal site with organically poor, pelagically derived sediments.

The sediment profile at the turbidite site is characterized by a largely undisturbed, 14-cm-thick turbidite layer, possessing different properties than those of the layers of highly bioturbated pelagic deposits above and below it. The turbidite layer exhibits graded bedding of sediment of larger grain size, lesser porosity, and lesser shear strength than those of the pelagic layers (Briggs et al. 1985). The rapid deposition of the turbidite layer apparently produced "a hiatus in bioturbation activity" and preserved intact the gradient of sediment properties that were "created and maintained by past biological activity" in the buried pelagic layer (Richardson et al. 1985). X-radiograph profiles of the interface between the turbidite layer and the lower pelagic layer (at 28 cm depth) exhibit biogenic features suggesting that several motile burrowers attempted, without success, to reach the new sediment surface and died (this hypothesized sequence is shown by the depositional event depicted in Fig. 5.4.2-1).

The sedimentation rate of pelagic-derived material since the episodic turbidity flow event was determined by activity profiles of uranium and thorium series isotopes to be 7.2 cm ky^{-1} (Cole et al. 1985). This rate suggests that the turbidity flow event occurred about two thousand years ago. The upper (0–14 cm depth) pelagic layer, overlying the turbidite layer, shows extensive biogenic structure in x-radiographs (Briggs et al. 1985). Radionuclide profiles show highest biogenic mixing rates for the upper 4–8 cm of this upper layer (Li et al. 1985). If we assume that 2 cm was the step length (mean vertical distance of particle displacement by bioturbation; see Wheatcroft 1990) characteristic of the upper pelagic layer during the first 1000 years following the turbidity flow, bioturbation by colonizing macrobenthos would rework up to 6.4 cm depth of accumulated sediment, but would not penetrate into the turbidite layer (Fig. 5.4.2-1, Stage 1). This interpretation is supported by the fact that the interface between the upper pelagic layer and turbidite layer is largely intact, except for a few burrows that penetrate it. Briggs et al. (1985) show a 2-cm-thick layer of an iron-rich layer that is more cohesive than the upper pelagic and lower turbidite layers, suggesting that it may have been a barrier to some deposit-feeders unable to burrow though it. Various analyses (Shaw and Johns 1985; Baird and White 1985) show that the turbidite sediment contains labile organic compounds that are potentially nutritious to deposit-feeders, so an inhibitory effect by the turbidite layer to benthic fauna is unlikely. That a few burrowing deposit-feeders have made excursions into the turbidite layer suggests that the energy expended to make deep burrows has metabolically repaid the cost of making them, *sensu* Jumars and Wheatcroft (1989).

In an analogy with shallow-water benthic succession stages (Rhoads et al. 1978), the early successional benthic "pioneers" would be followed by later successional benthic fauna that feed at greater depths within the sediment (Fig. 5.4.2-1, Stage 2). The interpretation that the turbidite site is in an intermediate "stage 2" condition, *sensu* Rhoads and Germano (1982), is supported by the observation that, "infrequent mixing probably extends to at

Figure 5.4.2-1. EPISODIC DEPOSITION SCENARIO



least 30 cm at the turbidite site where tube-dwelling polychaetes occasionally 'mine' organically rich turbidite deposits" (Richardson et al. 1985, p. 257). The later successional, "stage 3," benthic stage in shallow-water marine sediments is viewed as representing an "equilibrium assemblage" which is achieved after one to two years following a major disturbance (Rhoads and Germano 1982). The equilibrium benthic community is typically comprised of long-lived, large, deposit-feeding individuals that feed upon buried particles, thereby transporting material and gases deep within the sediment. (Note that the equilibrium assemblage may result in benthic fauna taxonomically different from those in the original benthic community.) Assuming the correctness of this analogy of deep-sea benthic succession with that demonstrated for shallow-water benthos, the time to reach an equilibrium benthic assemblage at the turbidite site in the central Venezuela Abyssal Plain has probably not yet been reached after two thousand years following the episodic depositional event that destroyed the original benthic community there. This view is also supported by the lower abundance and biomass of benthic fauna in relation to organic matter potentially available for consumption at the turbidite site relative to adjacent sedimentary provinces in the Venezuela Basin not impacted by turbidity flows (Briggs et al. 1994; Richardson and Young 1987).

An estimate of more than two thousand years for a deep-sea benthic community to reach equilibrium conditions after an episodic depositional event may appear to be unreasonably long until one considers that the sedimentation rate of 7.2 cm ky^{-1} at the turbidite site in the Venezuela Basin is high in comparison with the usual range of sedimentation rates (0.5–2.0 cm ky^{-1}) for abyssal plains (Stordal et al. 1985). In addition, the average bioturbation rate coefficient (900 cm^2 ky^{-1}) reported by Li et al. (1985) for the turbidite site is significantly higher than the range of bioturbation rate coefficients (37–129 cm^2 ky^{-1}) reported for sediments from the Hatteras Abyssal Plain (Stordal et al. 1985). There are strong positive correlations between sedimentation rates (and particulate organic carbon flux, see Jahnke and Jackson 1992) and bioturbation rates in the abyssal ocean (Smith, C. 1992). How the sudden influx of organically rich material would affect these correlations is unknown.

Smith, C. (1992) notes that increases of organic carbon flux to the abyssal seafloor would not only result in higher bioturbation rates, but greater depths of biogenic reworking because high amounts of organic matter are positively correlated to higher abundances, greater biomass, and larger mean body sizes of deposit-feeding benthic fauna in the deep sea. He concludes that even though the larger benthic fauna, the megabenthos, are much less abundant than the smaller macrobenthos, the deposit-feeding megabenthos appear to dominate the spatial and temporal scales of bioturbation and sediment-mixing depths, thereby controlling diffusion and advection of particles and solutes which affect rates of sediment diagenesis. In accordance with the findings by Wheatcroft et al. (1990), particle displacement would be expected to be farther in the horizontal than the vertical direction.

The time for recovery from an episodic deposition of material on the scale of a turbidity flow will vary according to the spatial scale (including the thickness) and characteristics (especially organic carbon content) of the turbidite material. On a time scale of hundreds to thousands of years, the equilibrium benthic community will probably consist of denser and larger animals with higher bioturbation rates and deeper mixing depths than those that existed prior to the depositional event. Thus, the new benthic community will be quantitatively and qualitatively different from the original community. These differences

will result in higher particle and solute fluxes reflecting changes in the geochemistry of the surface layer of the deposit controlled by the maximal depth of biogenic reworking. (Note that the geochemistry of deeper layers of the deposit will be dominated by molecular diffusion processes on the scale of thousands to tens of thousands of years as discussed in Section 5.3.4, **Prediction of Near- and Far-Field Effects Resulting from Introduction of Wastes to Abyssal Environments**.) How well these predictions may apply to the disposal of dredged material and sewage sludge in the deep ocean will depend on the volumes, composition, and packaging of waste material and the concept for delivery and containing the wastes on the abyssal seafloor.

5.4.2.4 Conclusions

Neither the episodic deposition scenario, as interpreted here for turbidite sediments, nor results from the small-scale seafloor experiments, as previously noted, will be strictly applicable to the smaller scale of disposal operations considered in this study (see Section 1.4.1, **Engineering Concept**). The input quantities of wastes assumed for predictions of geochemical responses (see Section 5.3.4) result in a deposit that is 1.2 km in diameter and 14 m thick at the center. We assume that resident macrobenthos, which are adapted to slow abyssal depositional rates of detritus, will probably be rapidly smothered and buried by any more than a few millimeters of waste at any time. Those megabenthic fauna that are able to maintain their burrows at the sediment-water interface may survive as long as depositional rates do not exceed several centimeters per week. If depositions of ten centimeters or more occur at any given time, given analogies of evidence from turbidite deposits, a total destruction of the benthic community will occur with the exception of many of the more mobile demersal fauna able to move away from the material being emplaced on the seafloor. Thus, at the end of a year-long emplacement operation of loose dredged spoil and sewage sludge, there will be no surviving benthic fauna except at the outer ring of the disposal pile.

We do not know the effect on benthic ecosystem recovery rates considering the high organic matter contents of dredged material and of sewage sludge, which can be as much as two orders of magnitude higher than the organic carbon contents of material received on the abyssal seafloor by natural sedimentation processes or by turbidity flows. What is currently known about abyssal benthic faunal responses to inputs of organic matter is inadequate to address these unknowns. In such cases, results and insight gained by numerical modeling and sensitivity testing are particularly useful. A carbon flux model (see Section 5.4.1, **Potential Export of Contaminants from Abyssal Waste Isolation Sites**) predicts that where inputs of material are not so great as to destroy the benthic fauna, remineralization of organic matter occurs quite rapidly, leading to a return to steady-state conditions in several years.

If depths of burial are such that there is a destruction of all benthic fauna, colonization from adult macrobenthic individuals could occur only on the periphery of the pile on scales of "ambit" areas (~0.01 m^2). Mobile megabenthos, such as the surface deposit-feeding holothurians, could be among the first of the benthic community to take advantage of organically rich surface deposits. Colonization by planktonic larvae of opportunistic, deposit-feeding macrobenthos could take place over the entire deposit within the first several years

following cessation of the disposal operation, depending upon how long hypoxic conditions may persist. Assuming the bottom water is well oxygenated, the length of time that hypoxic conditions will persist is a function of the volume and organic content of the deposit as well as the speed and direction of benthic boundary layer currents. Since the velocities of bottom currents at the selected sites which are optimal for waste isolation (see Section 5.1, **Physical Oceanography**) will be less than critical erosional velocities of the deposited material, reworking of the sediment and resulting seafloor roughness will be the result of bioturbation activities. Bioturbation of the deposition will result in smoothing of bottom roughness and lateral spread of deposited material, as well as increased oxygenation of the surface layer and metabolism of organic matter.

What little is known about successional events in the deep sea suggests that colonization by benthic fauna would take place (barring toxic or chemical inhibitory effects) within weeks following cessation of a disposal operation on the scale considered here; whereas, equilibrium conditions would be reached only after hundreds of years. Disposal of waste materials in bags would further delay this sequence of events depending upon the rates of deterioration of the bag material (see Section 1.4.2, **Bag Composition**). If responses by deep-sea benthic fauna to disturbances on the large scales of turbidity flows are any clue, it would be a preferable strategy to limit the size of deposition piles to no larger than that considered here (~1 km^2) to encourage colonization by benthic fauna and to minimize potentially detrimental geochemical changes. Disposal operations should encourage the maintenance of a patchy mosaic of deposition piles, as opposed to overlapping piles that would bury large contiguous areas of the abyssal seafloor.

6.0 COST ASSESSMENT *by Philip J. Valent*

6.1 Unit Costs Source-to-Site Including Monitoring

In presenting their cost estimates for the ocean option for waste management, the Woods Hole Oceanographic Institution (WHOI) noted that "...earlier studies on cost estimation for new technologies and detailed quantitative analyses of a number of pioneer projects have demonstrated that costs estimated for projects using commercially unproven technologies are not only characteristically biased low, but are so uncertain that they cannot be relied upon at all" (Marine Policy Center 1993). In conducting this SERDP study, the principal investigators have kept this WHOI study finding in mind when developing our cost estimates for the abyssal seafloor waste isolation option, and have been conservative in our projections.

This study's Technical Assessment Task (Hightower et al. 1995) estimated the cost of moving waste material from port to emplacement site by the least costly technique, the Surface Emplacement Concept, to be: for dredged material, $16/m^3 ($12/yd^3) and for sewage sludge and municipal waste fly ash, $15/metric ton (Hightower et al. 1995). This cost includes that for the construction and operation of the bulk carrier or integrated tug/barge to transport the waste and the cost of materials and fabrication for waste containers (fabric bags). It does not include the cost of technology and environmental understanding development required before the ocean option can be endorsed for implementation. Nor does this estimate include the cost of monitoring to ensure isolation of the waste during and after emplacement.

The Economic Assessment Task of this study (Jin et al. 1995) refined the port-to-site cost estimate and added to that estimate the cost estimate for moving the waste from source to port. Jin et al. (1995) excluded dredged material from consideration in their development of a cost estimate "...due to lack of data at the present time." They estimate the cost of transporting sewage sludge and municipal combined ash (fly and bottom ash) from the New York/New Jersey area to Atlantic-1 would be $43/metric ton. The source-to-port and port-to-site components of this cost vary significantly with the source-to-port haul distance. Source-to-port costs increase near-linearly with haul distance because variable costs, such as labor cost for truck drivers, are the driving cost elements for this component. On the other hand, port-to-site costs decrease with source-to-port haul distance because increasing the haul distance increases the tonnage (or volume) of wastes that can be gathered, and increased tonnage translates into increased efficiencies for the large marine bulk carriers used in the port-to-site component. Selected data from Jin et al. (1995), for sewage sludge and municipal waste fly ash for the New York/New Jersey area, illustrate the impact of source-to-port haul distance on the two cost components (Table 6.1-1). The difference in cost estimates for the port-to-site component between the Technical Assessment Task ($15/metric ton) and the Economic Assessment Task (between $24 and $33 per metric ton) is due primarily to a difference in port-to-site distance assumed in the analyses, i.e., the Technical Assessment Task assumed a port- to-site distance of 1060 km (575 nmi), the average of distances from major ports to the closest of the five Surrogate Sites, vice the Economic Assessment Task assumption of 1460 km (787 nmi), the distance from Port of

New York/New Jersey to Atlantic-1. The difference in Economic Assessment Task cost estimates for the port-to-site cost for different source-to-port distances (see Table 6.1-1) arises because the available annual tonnages of wastes vary with the source-to-port transport distance assumed: including wastes within 50 mi of the Port of New York/New Jersey gathers 1.8 million metric tons, whereas increasing the radius to 100 mi raises the tonnage to 3.0 million metric tons (Jin et al. 1995, p 33, 34).

Table 6.1-1. Combined cost of land and marine components for abyssal plain isolation of sewage sludge and municipal incinerator fly ash for New York/New Jersey area (source pages in Jin et al. 1995).

Source-to-Port Distance, mi	**50**	**100**	**Source**
Source-to-port cost, $/metric ton	10	19	p 50
Port-to-site cost, "	33		p 66
Port-to-site cost, "		24	p 70
Source-to-site cost, "	43	43	

As noted above, the Economic Assessment Task did not address the cost of dredged material isolation. The difficulty encountered in developing this cost estimate was that of separating the cost of dredging the sediment from the channel or harbor bed from the cost of transport and disposal: dredging, transport, and disposal costs are treated as one lumped cost. That lumped cost is reported to be $\$7–20/m^3$ ($\$5–15/yd^3$) for dredged material (uncontaminated?) placed offshore, and $\$7–33/m^3$ ($\$5–25/yd^3$) for dredged material (uncontaminated?) placed in the harbor area (Hoskins and Silva 1994). Working from these cost data, and as a very preliminary estimate, we assume herein that the cost of dredging contaminated sediments, using best clean dredging equipment and techniques and good turbidity containment devices, will be $\$10/m^3$. Converting the port-to-site cost for 1.8 million metric tons of material from Table 6.1-1 ($33/metric ton) from $/metric ton to $\$/m^3$ for dredged material (with bulk density of 1.25 Mg/m^3) yields a unit cost of $\$41/m^3$. Then a cost estimate for abyssal seafloor isolation of dredged material is:

Dredging cost	$\$10/m^3$
Transport and Emplacement cost	41
Dredged material isolation cost	$\$51/m^3$

The above costs total those costs for construction and operation of facilities and platforms for the isolation of wastes on the abyssal seafloor. To these costs must be added those

for monitoring the sites during and after waste emplacement. In Section 4.6 of this report, the cost of such monitoring was projected to be \$12.60/metric ton (ca. \$13/metric ton or /m^3). Including monitoring costs into our cost estimates for waste isolation yields:

Waste Material	Sewage Sludge and Fly Ash	Dredged Material
Land and marine transport	\$43/metric ton	\$51/m^3
Waste site monitoring	13	13
Total, transport and monitoring	\$56/metric ton	\$64/m^3

The projected cost of \$56 per metric ton for isolation of sewage sludge on the abyssal seafloor is competitive with present land-based disposal costs in New York City of over \$160 per ton (Jin et al. 1995). The projected cost of \$56 per metric ton for fly ash is less than competitive with present land-disposal costs for the New York area of \$48 per ton (Jin et al. 1995). However, the abyssal seafloor option proposes use of the fly ash as a weighting material to increase the bulk density of the sewage sludge; and, when used for this purpose, the fly ash would, in effect, be serving in a beneficial use. The projected cost of \$64/m^3 for isolation of contaminated dredged material on the abyssal seafloor is competitive with present upland site disposal costs of \$130–330/m^3 (\$100–250/yd^3) (Hoskins and Silva 1994), where the higher end costs are likely those representing costs for contaminated dredged material requiring disposal in lined upland sites. Hoskins and Silva (1994) also note that treatment through chemical means or incineration cost \$200–1,300/m^3 (\$150–1,000/yd^3), a cost considerably more than that of the abyssal seafloor waste isolation option.

6.2 Science and Technology Development Costs

The cost estimates of Section 6.1 are those covering the construction and fabrication of a tested and proven concept for the transport and emplacement of wastes, the operation of that concept, and the monitoring of the effectiveness of waste isolation at the site. Not included in these cost estimates is the research and development cost associated with developing the transport and emplacement concept technology to the degree where design for construction is straightforward, and with developing our understanding of physical, chemical, and biological oceanography to the extent where trusted models of processes are available and environmental responses to perturbations, such as high organic input, can be predicted.

Hightower et al. (1995), p 30, estimate abyssal seafloor waste isolation technology development costs, i.e., component testing for the Surface Emplacement Concept, to require \$1M to \$5M. The Environmental Assessment Task team adds \$2M to these technology development costs, for development of monitoring systems and techniques, arriving at a total technology development cost of \$3M to \$7M.

Prior to implementation of the abyssal seafloor option, considerable in situ and laboratory research is required to improve, develop, and/or calibrate physical, chemical, and biological models describing processes that will ensue with and after emplacement of 1 to 2 million

metric tons of sewage sludge/fly ash combination and/or dredged material. The research program required is expected to cost $2M to $3M per year over a 5-year program, for a total research program cost of $9M to $12M. The total technology and science development costs of the abyssal seafloor waste isolation option implementation are then projected to be:

Technology development	$ 3M to $ 7M
Science understanding development	9 to 12
Total science and technology development	$12M to $19M

7.0 CONCLUSIONS *by David K. Young and Philip J. Valent*

(1) The principal conclusion from the Technical Assessment Task of the Abyssal Plains Waste Isolation Project is that the Abyssal Seafloor Waste Isolation concept is technically feasible using current technology (Hightower et al. 1995a; 1995b).

(2) The waste material is preferably to be contained in synthetic fabric, bag-like containers during passage through the water column and impact with the abyssal sediment seafloor. The three more technically attractive waste emplacement techniques are proposed to contain the waste material within such synthetic fabric containers. The technically most attractive technique for waste emplacement is to free-fall such containers from the ocean surface from a barge transporter. The two other techniques use remotely operating, unmanned submersibles to carry the waste-filled containers to near the seafloor before release: one submersible follows a near-45° path to and from the seafloor, and the other a near-vertical path. Given the conclusion that synthetic fabric bag containers will be used to emplace the wastes, these added conclusions pertinent to waste isolation site survey, assessment, selection, and monitoring are made:

(a) A technically feasible size for emplacement of wastes at an abyssal depth waste isolation site is an area 3000 m × 3000 m or a circle of 3000 m diameter. The selection of waste site size made at the beginning of this study, 500 m × 500 m, is too small. The technically feasible waste emplacement techniques are not capable of consistently placing the waste-filled containers within an area 500 m × 500 m.

(b) The resulting waste material deposit on the abyssal seafloor will likely include a significant volume of uncontained waste material from containers ruptured on the seafloor. Manufacturer and U.S. Army Corps of Engineers experience with dredged material filled bag containers indicate that the waste-filled containers will not rupture upon landing on the seafloor sediments. However, bag containers may land on other bag containers in a waste isolation site and may themselves rupture or cause the containers beneath to rupture.

(c) Sewage sludge, with its bulk wet density of 1.04 Mg/m^3, must be combined with another, more dense material to ensure a reasonable free-fall rate of waste-filled containers through the water column and accurate emplacement within the designated isolation site.

(d) Mixing of the sewage sludge and weighting material will likely not be complete, thus rupture of the bag containers could result in the sewage sludge component being transported by even the very-low-velocity currents expected near the seafloor at an abyssal seafloor waste site.

(3) The Abyssal Seafloor Waste Isolation concept is projected to be economically competitive with present-day waste management techniques for higher-priced areas, such as the New York/New Jersey area (Hightower et al. 1995b; 1995c; Jin et al. 1995; Section 6.0 of this report).

(4) The Abyssal Seafloor Waste Isolation concept is environmentally manageable with regard to site survey and monitoring considerations. It is accepted that the immediate area

of waste emplacement/isolation will be profoundly affected; far-field effects are expected to be minimal.

(5) The site selection model, described in Section 3.0, indicated that the majority of sites and the most favorable sites for waste isolation are in the Atlantic, indicated fewer and less favorable sites are in the Pacific, and indicated the least number and least favorable sites are in the Gulf of Mexico. For this analysis and comparison, the seafloor was divided into squares of 1° latitude by 1° longitude. Results specific to Atlantic, Pacific, and Gulf of Mexico are:

(a) The most favorable 1° squares in the Atlantic for isolation are in the Hatteras Abyssal Plain and next best in the Nares Abyssal Plain. These areas rank high because of favorable sediment type, low currents, favorable weather, and relatively low biologic and anthropogenic activity.

(b) The most favorable 1° squares in the Pacific are found in level, low relief regions of the pelagic clay, abyssal hills province between the Murray and Molokai Fracture Zones. This area ranks high for reasons similar to those given for the Atlantic.

(c) Only 19 1° squares are open for consideration in the Gulf of Mexico after application of the 3000-m water depth and the Mexican EEZ exclusions. Excluding squares with high-densities of ship traffic reduces the number of 1° squares open for consideration to 13. Of these 13, the highest-ranking square is on the northern Sigsbee Abyssal Plain, and the second-highest-ranking is on the southeastern Mississippi cone.

(6) Model predictions suggest that for likely waste isolation scenarios the emplaced wastes will:

(a) be contained physically within a defined site,

(b) profoundly impact geochemical processes at a site for thousands to tens-of-thousands of years,

(c) wipe out the existing fauna impacted directly by large amounts of waste materials (these fauna will be replaced by a new benthic community; recruitment will start within weeks following cessation of waste emplacement operations, assuming no toxic or inhibitory effects), and

(d) result in a new equilibrium benthic community after hundreds to thousands of years; this community may consist of denser and larger fauna.

(7) Emplacement of waste materials in synthetic fabric containers will further delay the predicted foregoing sequence of events, with the length of that delay depending upon the rates of deterioration of the container material. It is possible that the high-pressure, low-temperature, and low-energy environment of the abyssal ocean will greatly extend the normally long life of the synthetic fabric material.

(8) Waste emplacement operations should encourage the maintenance of a patchy mosaic of emplaced waste piles, as opposed to overlapping piles which would bury large contiguous areas of the abyssal seafloor. Such patchy distribution is expected to encourage colonization by benthic fauna and to minimize potentially detrimental geochemical changes.

(9) Potential contaminants associated with the wastes are not expected to enter into food chains utilized by humans; if some should, the amounts will be very small and likely not detectable. The only potential export of contaminants, albeit very small, from the deep sea into surface waters would be via lecithotropic (yolk-containing) eggs or larvae. This conclusion assumes that sewage sludge, because of its near-neutral buoyancy, will be contained in weighted geotextile containers to ensure that the sludge stays where placed, or assumes that the sludge is thoroughly blended with a weighting material to ensure that no portion of the sludge will float away from the placement site (see Section 1.4.1.2, pp. 25 and 27).

(10) There is a strong possibility that the high sorptive capacity of organic-rich, fine-grained, waste materials will lead to immobilization of many chemical contaminants (e.g., heavy metals, organic compounds). Further work is needed to identify those contaminants that may be leachable or bioavailable upon ingestion from the placed material, either individually or in combination with other material components.

There are uncertainties and unknowns with regard to many of these conclusions. Some conclusions are based largely on inference and model predictions; these necessitate validation by measurements.

8.0 RECOMMENDATIONS *by Philip J. Valent and David K. Young*

(1) All of the techniques selected for transporting the waste materials to the seafloor employ synthetic-fabric (geotextile) bag-like containers. Research must be undertaken to gain the capability to make reliable estimates of the long- and short-term performance of these geotextile containers, principally in two areas: (a) hydrodynamic responses to release from the platform, free-fall through the water column, and landing/impact on the seafloor sediments and (b) responses of the geotextile materials to the physical, chemical, and biological stresses caused by the combination of contained wastes and abyssal environment. This research would include physical modeling of the waste-filled container hydrodynamic performance/stability in free-fall, accelerated deterioration testing of the container fabric and stitching in the laboratory, and in situ testing of the resistance/performance of the fabric and stitching to biologic degradation and penetration of the fabric and/or seams.

(2) A long-term commitment to measurement and prediction of the abyssal seafloor environment is required. This should include coordinated efforts in the collection of current data near the seafloor for quantifying long-term transports of suspended and dissolved substances, seafloor-scouring events, and turbulent plume transports.

(3) A moderate-sized investment is required to gain the capability to model, in four dimensions, the physical, chemical, and biological environment of the abyssal seafloor when that environment is perturbed by rapidly placed, large-volume deposits of highly organic, fine-grained material. A follow-on investment for site selection and monitoring of a demonstration abyssal isolation site would be model-driven in that the monitoring program would cross all disciplines. The field experiment would generate data which would either validate the models or cause a redefinition of model parameters, or indeed, revised working hypotheses themselves. Nonpolluting tracers should be added to this test material to mimic performance of potential anthropogenic contaminants.

(4) The potential for methane clathrate formation within candidate highly organic waste materials should be investigated in the laboratory at abyssal seafloor pressures and temperatures and expected waste permeabilities. This work should assess the potential for methane clathrate formation due to: (a) the methane generated and contained within the waste at the time of emplacement, and (b) that methane generated after emplacement of the dredged material on the seafloor.

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APPENDIX A:

GEOREFERENCED 1° CELL MAP SCORES FROM SITE SELECTION MODEL FOR ISOLATION SCENARIO AND FOR EXAMPLE DISPERSAL AND LOGISTICS SCENARIOS

WESTERN NORTH ATLANTIC

GULF OF MEXICO

EASTERN NORTH PACIFIC

latitude/longitude at centers of 1° squares

	-82.5	-81.5	-80.5	-79.5	-78.5	-77.5	-76.5	-75.5	-74.5	-73.5	-72.5	-71.5	-70.5	-69.5	-68.5	-67.5	-66.5	-65.5
45.5																		
44.5															0	0	0	
43.5													0	0	0	0	0	0
42.5													0	0	0	0	0	0
41.5												0	0	0	0	0	0	0
40.5										0	0	0	0	0	0	0	38.499	45.374
39.5									0	0	0	0	0	0	48.249	42.374	0	50.249
38.5									0	0	0	0	33.874	51.874	54.374	57.499	54.374	54.874
37.5								0	0	0	45.374	51.874	54.749	46.124	42.999	56.999	57.999	57.749
36.5								0	0	44.624	56.624	59.999	62.124	58.249	0	58.874	63.748	61.749
35.5								0	0	52.374	63.498	60.249	63.123	62.623	65.248	63.373	65.873	67.748
34.5						0	0	0	47.124	45.249	62.249	61.499	65.248	65.373	67.873	73.123	0	0
33.5					0	0	0	44.624	63.248	59.999	49.499	67.373	75.998	76.998	80.498	0	0	0
32.5		0	0	0	0	0	0	55.624	63.123	62.873	72.748	65.498	81.248	76.998	0	0	0	0
31.5		0	0	0	0	0		62.374	65.748	68.498	80.498	63.748	83.248	0	0	0	0	0
30.5		0	0	0	0	0	56.749	73.623	67.748	67.748	77.248	68.248	83.248	80.748	0	0	0	0
29.5		0	0	0	0	0	50.374	72.373	78.623	68.998	75.998	69.248	89.248	81.748	0	71.998	74.498	0
28.5			0	0	0	0	52.374	0	77.373	75.373	0	77.248	85.998	0	78.748	77.998	74.498	74.498
27.5				0	0	0	0	0	0	71.623	0	79.748	88.498	0	79.748	77.998	75.498	74.498
26.5				0	0	0	0	0	0	0	0	83.623	89.248	0	77.998	77.998	77.998	77.248
25.5				0	0	0	0	0	0	0	0	87.248	87.873	0	0	77.998	77.248	77.248
24.5		0	0	0	0	0	0	0	0	0	0	0	0	79.248	79.748	0	77.998	77.998
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	73.498	76.873	83.998
22.5				0	0	0	0	0	0	0	0	0	0	0	0	72.248	79.873	84.748
21.5						0	0	0	0	0	0	0	0	0	0	0	0	0
20.5									0	0	0	0	0	0	0	0	0	0
19.5														0	0	0	0	0
18.5															0	0	0	0
17.5																		

WESTERN NORTH ATLANTIC, part 1 **ISOLATION SCENARIO** **PERCENT SCORES**

latitude/longitude at centers of 1° squares

-64.5	-63.5	-62.5	-61.5	-60.5	-59.5	-58.5	-57.5	-56.5	-55.5	-54.5	-53.5	-52.5	-51.5	-50.5	-49.5	-48.5	-47.5	
																		45.5
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**44.5**
0	0	0	0	0	0	0	38.624	35.374	39.999	38.874	0	0	0	0	0	0		**43.5**
0	0	0	0	0	51.499	55.249	58.624	43.499	44.749	44.999	40.749	0	0	0	0	0		**42.5**
0	0	0	55.374	56.749	56.124	58.499	59.999	42.624	43.874	45.624	46.874	40.749	0	0	0	0		**41.5**
0	51.999	52.499	54.374	54.249	64.123	60.624	64.873	47.749	48.749	48.124	52.374	43.874	0	0	0	0		**40.5**
52.499	53.624	59.499	55.999	0	55.499	49.249	49.249	49.249	51.749	52.499	53.124	49.624	0	0	0	0		**39.5**
0	0	55.124	0	0	52.624	59.999	58.374	69.373	61.874	61.874	61.124	61.874	61.249	61.249	0	0		**38.5**
60.874	60.749	57.749	59.124	0	56.999	51.624	62.748	62.748	58.374	58.374	61.874	60.624	63.373	63.998	54.374	0		**37.5**
58.874	65.498	63.123	63.123	60.874	61.999	61.999	66.248	66.248	66.373	63.373	58.374	55.624	62.374	60.624	0	0		**36.5**
64.373	63.998	60.249	63.748	66.248	64.998	63.248	60.749	61.874	63.748	65.498	56.249	52.999	57.874	59.249	0	0		**35.5**
0	0	0	66.498	65.248	65.748	66.998	60.749	60.124	68.498	68.998	61.499	58.249	63.748	0	0	0		**34.5**
0	0	0	0	63.998	66.998	66.998	60.749	65.373	68.998	68.998	69.748	68.998	0	0	0	0		**33.5**
0	0	0	0	0	0	69.998	62.623	72.248	71.498	68.998	71.498	0	0	0	0	0		**32.5**
0	0	0	0	0	74.998	0	74.998	74.998	74.998	77.498	0	0	0	0	0	0		**31.5**
0	0	0	75.748	74.998	0	73.248	75.748	75.748	74.998	0	0	0	0	0	0	0		**30.5**
0	0	74.498	74.998	0	0	0	0	0	0	0	0	0	0	0	0	0		**29.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**28.5**
74.498	73.873	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**27.5**
74.498	78.373	78.998	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**26.5**
0	73.873	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**25.5**
77.998	73.873	73.373	76.998	0	0	0	0	0	0	0	0	0	0	0	0	0		**24.5**
83.998	79.873	76.998	81.248	0	0	0	0	0	0	0	0	0	0	0	0	0		**23.5**
84.748	79.873	76.248	71.998	0	0	0	0	0	0	0	0	0	0	0	0	0		**22.5**
0	0	71.998	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**21.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**20.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**19.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**18.5**
																		17.5

WESTERN NORTH ATLANTIC, part 2 **ISOLATION SCENARIO** **PERCENT SCORES**

latitude/longitude at centers of 1° squares

	-98.5	-97.5	-96.5	-95.5	-94.5	-93.5	-92.5	-91.5	-90.5	-89.5	-88.5	-87.5	-86.5	-85.5	-84.5	-83.5	-82.5	-81.5	-80.5	-79.5
31.5																				
30.5										0	0	0	0							
29.5					0	0	0	0	0	0	0	0	0	0	0	0				
28.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
27.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
26.5		0	0	0	0	0	0	0	59.749	60.499	0	0	0	0	0	0	0	0		
25.5		0	0	0	0	66.248	65.998	65.998	68.748	68.748	58.249	54.499	66.748	0	0	0	0	0	0	
24.5		0	0	0	0	71.123	0	0	0	0	0	0	0	70.748	58.499	0	0	0	0	
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0					
21.5		0	0	0	0	0	0	0	0	0	0	0	0							
20.5			0	0	0	0	0	0	0											
19.5			0	0	0	0	0	0												
18.5					0	0														
17.5																				

GULF OF MEXICO

ISOLATION SCENARIO

PERCENT SCORES

latitude/longitude at centers of squares

	-150.5	-149.5	-148.5	-147.5	-146.5	-145.5	-144.5	-143.5	-142.5	-141.5	-140.5	-139.5	-138.5	-137.5	-136.5	-135.5	-134.5	-133.5	-132.5	-131.5	-130.5	-129.5	-128.5	-127.5	-126.5	-125.5
60.5																										
59.5		0	0	0	0	0	0	0	0	0	0	0														
58.5		0	0	0	0	0	0	0	0	0	0	0	0	0												
57.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0											
56.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
55.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0									
54.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
53.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
52.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
51.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
50.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
49.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64.75	65.87	0	65.12	64	62.12	61	58.37	50.37	41.5
38.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	67.75	63.62	63.5	60.75	61.87	48.37
37.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66.5	62.12	61	61.37	61.37	53.5
36.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77.75	77.12	76.5	75.87	76.5	75.62	68	62	62	48.5
35.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77.12	76	0	0	76.25	64.5	64.5	55.5
34.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	71.75	76.75	77.12	76.62	77.75	74.87	76.62	75.12	67.62	67.25	64.87
33.5		0	0	0	0	0	0	0	0	77.75	77.12	76.5	74	75.37	77.12	76	75.5	79	75	0	0	0	0	0	67	65.12
32.5		0	0	0	0	0	0	77.62	77.12	74	74	75.75	76.37	74.62	0	0	0	0	0	0	0	0	72.5	68	67.5	65.37
31.5		0	0	0	0	0	0	0	0	72.87	76.37	0	0	0	0	0	0	0	0	0	0	0	80.5	69.25	67.5	65.75
30.5		0	0	0	0	0	0	0	77	78.87	78.87	78.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29.5		0	0	0	0	0	0	0	81.25	84.25	81.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28.5		0	0	0	0	0	0	0	0	0	0	0	81.25	81.87	0	0	0	0	0	0	0	0	0	0	0	0
27.5		0	0	0	0	0	0	0	0	0	78.25	79.37	82.5	82.5	0	0	0	0	0	0	0	82.12	83.25	80.5	80.5	75.37
26.5		0	0	0	0	0	0	0	0	0	0	82.5	81.25	81.25	81.25	81.25	0	0	0	0	81.37	83.25	82.12	81.87	83	76.5
25.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	80.12	78.75	81.25	80.5	81.25	81.25	81.25	0	0	0	75.25
24.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	79	80.12	81.25	0	0	0	0	0	0	0	0
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79.87	0	0	0	0	0
21.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	78.37	74.12
18.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5																										

EASTERN NORTH PACIFIC, part 1

ISOLATION SCENARIO

PERCENT SCORES

latitude/longitude at centers of squares

-124.5	-123.5	-122.5	-121.5	-120.5	-119.5	-118.5	-117.5	-116.5	-115.5	-114.5	-113.5	-112.5	-111.5	-110.5	-109.5	-108.5	-107.5	-106.5	-105.5	-104.5	-103.5	-102.5	-101.5	-100.5	
																									60.5
																									59.5
																									58.5
																									57.5
																									56.5
																									55.5
																									54.5
																									53.5
																									52.5
																									51.5
																									50.5
																									49.5
0	0																								48.5
0	0	0																							47.5
0																									46.5
0																									45.5
0																									44.5
0																									43.5
0																									42.5
0																									41.5
0																									40.5
0	0																								39.5
46	0	0																							38.5
52.75	34.5	0	0																						37.5
45.25	43.25	36.75	0																						36.5
57.75	53.87	48.12	0	0																					35.5
63.62	57.12	53.25	36.25	0	0																				34.5
66.25	60.75	62.25	55.25	0	0	0	0																		33.5
66	68	68.75	59.75	57.75	0	0	0																		32.5
67.5	65.5	64.37	61.12	64.25	0	0	0	0		0															31.5
67.25	64.62	64.62	63.75	0	0	0	0	0		0	0														30.5
0	0	0	0	0	0	0	0	0	0		0	0													29.5
0	0	70.75	68.75	0	0	0	0	0	0		0	0	0												28.5
76.5	69	66.5	66.75	0	0	0	0	0	0			0	0	0											27.5
76.5	74.5	70.5	63.87	0	0	0	0	0	0	0	0		0	0	0										26.5
75.25	0	73.25	70.12	79	0	0	0	0	0	0	0	0		0	0	0									25.5
0	0	73.75	71.25	0	0	0	0	63.12	0	0	0	0		0	0	0	0								24.5
0	0	75.5	73.75	0	0	0	0	63.5	60.25	0	0	0	0	0	0	0	0								23.5
0	76.75	77.5	72.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							22.5
0	77.5	73.87	68.87	76.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						21.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							20.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						19.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				18.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		17.5
																									16.5

EASTERN NORTH PACIFIC, part 2 — ISOLATION SCENARIO — PERCENT SCORES

latitude/longitude at centers of 1° squares

	-82.5	-81.5	-80.5	-79.5	-78.5	-77.5	-76.5	-75.5	-74.5	-73.5	-72.5	-71.5	-70.5	-69.5	-68.5	-67.5	-66.5	-65.5
45.5																		
44.5															0	0	0	
43.5													0	0	0	0	0	0
42.5													0	0	0	0	0	0
41.5												0	0	0	0	0	0	0
40.5										0	0	0	0	0	0	0	49.249	38.874
39.5									0	0	0	0	0	0	43.249	41.124	0	36.749
38.5									0	0	0	0	55.124	37.624	36.374	34.749	32.874	32.624
37.5								0	0	0	44.374	40.374	36.499	46.374	49.999	35.999	34.999	28.499
36.5								0	0	44.874	41.374	36.999	35.124	36.499	0	37.374	38.499	35.999
35.5								0	0	43.624	35.249	37.249	34.374	34.624	37.749	32.874	36.374	36.249
34.5						0	0	0	44.624	53.999	37.249	38.249	34.249	32.874	33.874	29.874	0	0
33.5					0	0	0	48.874	37.249	39.499	49.749	32.874	31.499	29.749	27.999	0	0	0
32.5		0	0	0	0	0	0	46.874	37.374	35.624	29.499	42.999	27.249	29.749	0	0	0	0
31.5		0	0	0	0	0	0	47.124	41.249	31.999	27.999	39.749	21.249	0	0	0	0	0
30.5		0	0	0	0	0	56.999	35.874	37.999	37.999	31.499	36.249	21.249	26.999	0	0	0	0
29.5		0	0	0	0	0	55.874	34.624	27.874	39.249	38.249	45.499	27.249	27.999	0	29.749	32.249	0
28.5			0	0	0	0	52.624	0	31.624	32.624	0	31.499	25.499	0	34.999	35.749	32.249	32.249
27.5				0	0	0	0	0	0	33.874	0	33.999	27.999	0	33.999	35.749	39.999	32.249
26.5				0	0	0	0	0	0	0	0	29.874	27.249	0	35.749	35.749	35.749	36.499
25.5				0	0	0	0	0	0	0	0	26.749	27.374	0	0	35.749	36.499	36.499
24.5		0	0	0	0	0	0	0	0	0	0	0	0	31.999	33.999	0	35.749	35.749
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	39.249	36.624	31.499
22.5				0	0	0	0	0	0	0	0	0	0	0	0	37.999	32.624	30.749
21.5						0	0	0	0	0	0	0	0	0	0	0	0	0
20.5									0	0	0	0	0	0	0	0	0	0
19.5														0	0	0	0	0
18.5															0	0	0	0
17.5																		

WESTERN NORTH ATLANTIC, part 1 **DISPERSAL SCENARIO** **PERCENT SCORES**

latitude/longitude at centers of 1° squares

-64.5	-63.5	-62.5	-61.5	-60.5	-59.5	-58.5	-57.5	-56.5	-55.5	-54.5	-53.5	-52.5	-51.5	-50.5	-49.5	-48.5	-47.5	
																		45.5
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**44.5**
0	0	0	0	0	0	0	53.624	60.124	55.749	56.624	0	0	0	0	0	0		**43.5**
0	0	0	0	0	39.999	36.999	32.124	46.999	46.249	45.249	51.249	0	0	0	0	0		**42.5**
0	0	0	34.874	34.749	35.624	33.999	30.249	48.374	47.624	45.874	44.124	51.249	0	0	0	0		**41.5**
0	32.999	31.499	31.874	29.749	26.124	27.874	25.374	42.249	45.999	45.374	42.874	51.374	0	0	0	0		**40.5**
30.999	32.124	26.749	30.749	0	30.999	39.749	39.749	39.749	42.249	41.749	42.374	44.124	0	0	0	0		**39.5**
0	0	37.124	0	0	35.374	34.249	37.874	28.624	36.124	36.124	36.624	36.124	35.499	35.249	0	0		**38.5**
26.874	27.999	38.249	37.374	0	37.749	41.374	32.249	32.249	37.874	37.874	36.124	36.374	35.124	35.749	30.124	0		**37.5**
31.124	31.999	32.374	32.374	36.874	37.499	39.499	31.999	31.999	30.624	32.874	37.874	43.124	36.124	32.874	0	0		**36.5**
39.374	34.999	38.249	32.999	31.499	32.249	38.749	36.249	31.124	29.499	27.749	36.999	41.999	37.624	35.999	0	0		**35.5**
0	0	0	27.249	27.999	27.999	29.249	36.249	36.124	26.749	25.249	32.749	37.749	32.749	0	0	0		**34.5**
0	0	0	0	31.499	29.249	29.249	36.249	31.874	26.749	33.499	32.749	33.499	0	0	0	0		**33.5**
0	0	0	0	0	0	34.499	31.874	28.499	29.249	33.499	29.249	0	0	0	0	0		**32.5**
0	0	0	0	0	34.249	0	32.749	32.749	32.749	30.249	0	0	0	0	0	0		**31.5**
0	0	0	33.499	34.249	0	37.749	33.499	33.499	32.749	0	0	0	0	0	0	0		**30.5**
0	0	32.249	34.249	0	0	0	0	0	0	0	0	0	0	0	0	0		**29.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**28.5**
32.249	31.624	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**27.5**
32.249	28.124	28.749	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**26.5**
0	31.624	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**25.5**
35.749	31.624	33.124	29.749	0	0	0	0	0	0	0	0	0	0	0	0	0		**24.5**
31.499	27.374	29.749	27.249	0	0	0	0	0	0	0	0	0	0	0	0	0		**23.5**
30.749	27.374	30.499	29.749	0	0	0	0	0	0	0	0	0	0	0	0	0		**22.5**
0	0	29.749	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**21.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**20.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**19.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**18.5**
																		17.5

WESTERN NORTH ATLANTIC, part 2 **DISPERSAL SCENARIO** **PERCENT SCORES**

latitude/longitude at centers of 1° squares

	-98.5	-97.5	-96.5	-95.5	-94.5	-93.5	-92.5	-91.5	-90.5	-89.5	-88.5	-87.5	-86.5	-85.5	-84.5	-83.5	-82.5	-81.5	-80.5	-79.5
31.5																				
30.5										0	0	0	0							
29.5					0	0	0	0	0	0	0	0	0	0	0	0				
28.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
27.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
26.5		0	0	0	0	0	0	0	41.999	42.749	0	0	0	0	0	0	0	0		
25.5		0	0	0	0	38.999	39.249	39.249	36.499	36.499	48.499	47.749	35.249	0	0	0	0	0	0	
24.5		0	0	0	0	35.624	0	0	0	0	0	0	0	36.499	46.999	0	0	0	0	
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0					
21.5		0	0	0	0	0	0	0	0	0	0	0	0							
20.5			0	0	0	0	0	0	0											
19.5			0	0	0	0	0	0												
18.5					0	0														
17.5																				

GULF OF MEXICO **DISPERSAL SCENARIO** **PERCENT SCORES**

latitude/longitude at centers of squares

	-150.5	-149.5	-148.5	-147.5	-146.5	-145.5	-144.5	-143.5	-142.5	-141.5	-140.5	-139.5	-138.5	-137.5	-136.5	-135.5	-134.5	-133.5	-132.5	-131.5	-130.5	-129.5	-128.5	-127.5	-126.5	-125.5
60.5																										
59.5		0	0	0	0	0	0	0	0	0	0	0														
58.5		0	0	0	0	0	0	0	0	0	0	0	0	0												
57.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0											
56.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
55.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0									
54.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
53.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
52.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
51.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
50.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
49.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42.25	41.37	0	42.62	43.5	44.87	45.75	50.62	54.12	61.75
38.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41.25	45.37	43.25	47	44.62	53.62
37.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.25	38.37	40.75	42.62	47.62	57.25
36.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29.5	28.87	28.25	27.62	28.25	30.87	34.75	42.25	42.25	59
35.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28.87	29.75	0	0	31.5	44.75	44.75	51.25
34.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	34.25	29	28.87	30.37	29.5	33.87	30.37	38.87	47.37	47.5	48.37
33.5		0	0	0	0	0	0	0	0	29.5	28.87	28.25	32.5	29.12	28.87	29.75	31.25	34.75	40	0	0	0	0	0	46.75	49.37
32.5		0	0	0	0	0	0	29.12	28.87	32.5	32.5	29	29.62	33.12	0	0	0	0	0	0	0	0	39.25	47	48.5	52.37
31.5		0	0	0	0	0	0	0	0	33.37	29.62	0	0	0	0	0	0	0	0	0	0	0	33.5	44.75	49.75	53.5
30.5		0	0	0	0	0	0	0	37.5	36.37	36.37	36.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29.5		0	0	0	0	0	0	0	33	29.5	30.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28.5		0	0	0	0	0	0	0	0	0	0	0	30	30.62	0	0	0	0	0	0	0	0	0	0	0	0
27.5		0	0	0	0	0	0	0	0	0	35.75	34.87	31.25	31.25	0	0	0	0	0	0	0	32.87	32	35.75	35.75	42.12
26.5		0	0	0	0	0	0	0	0	0	0	31.25	30	30	30	30	0	0	0	0	32.12	32	32.87	33.12	32.25	41.25
25.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	30.87	34.25	30	30.75	30	30	30	0	0	0	40
24.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	31.75	30.87	30	0	0	0	0	0	0	0	0
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37.37	0	0	0	0	0
21.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34.87	32.12
18.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5																										

EASTERN NORTH PACIFIC, part 1

DISPERSAL SCENARIO

PERCENT SCORES

latitude/longitude at centers of squares

-124.5	-123.5	-122.5	-121.5	-120.5	-119.5	-118.5	-117.5	-116.5	-115.5	-114.5	-113.5	-112.5	-111.5	-110.5	-109.5	-108.5	-107.5	-106.5	-105.5	-104.5	-103.5	-102.5	-101.5	-100.5	
																									60.5
																									59.5
																									58.5
																									57.5
																									56.5
																									55.5
																									54.5
																									53.5
																									52.5
																									51.5
																									50.5
																									49.5
0	0																								48.5
0	0	0																							47.5
0																									46.5
0																									45.5
0																									44.5
0																									43.5
0																									42.5
0																									41.5
0																									40.5
0	0																								39.5
56.5	0	0																							38.5
58	72.5	0	0																						37.5
65.5	68.75	74.75	0																						36.5
53.5	57.62	63.12	0	0																					35.5
50.62	52.87	57	74.25	0	0																				34.5
48.5	58	58	65.75	0	0	0	0																		33.5
51	49.5	49	62.25	64.75	0	0	0																		32.5
50	53.75	54.62	58.87	61.5	0	0	0	0		0															31.5
52.25	54.37	54.37	56.75	0	0	0	0	0		0	0														30.5
0	0	0	0	0	0	0	0	0	0		0	0													29.5
0	0	47	49	0	0	0	0	0	0		0	0	0												28.5
41.25	48.75	53	48.5	0	0	0	0	0	0			0	0	0											27.5
41.25	40.75	46	52.87	0	0	0	0	0	0	0	0		0	0	0										26.5
40	0	39.5	44.12	40.75	0	0	0	0	0	0	0	0		0	0	0									25.5
0	0	39	43.25	0	0	0	0	58.12	0	0	0	0		0	0	0	0								24.5
0	0	37.25	39	0	0	0	0	51.25	56	0	0	0	0	0	0	0	0								23.5
0	31.5	30.75	37.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							22.5
0	30.75	35.87	42.87	40.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						21.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							20.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						19.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				18.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		17.5
																									16.5

EASTERN NORTH PACIFIC, part 2

DISPERSAL SCENARIO

PERCENT SCORES

latitude/longitude at centers of 1° squares

	-82.5	-81.5	-80.5	-79.5	-78.5	-77.5	-76.5	-75.5	-74.5	-73.5	-72.5	-71.5	-70.5	-69.5	-68.5	-67.5	-66.5	-65.5
45.5																		
44.5															0	0	0	
43.5													0	0	0	0	0	0
42.5													0	0	0	0	0	0
41.5												0	0	0	0	0	0	0
40.5										0	0	0	0	0	0	0	42.819	40.537
39.5									0	0	0	0	0	0	54.303	47.076	44.833	42.576
38.5									0	0	0	0	54.514	52.627	50.613	51.018	43.871	41.69
37.5								0	0	0	57.276	56.253	52.376	50.748	48.944	47.019	45.005	37.932
36.5								0	0	52.354	54.417	53.593	52.443	48.534	46.93	47.678	50.813	43.861
35.5								0	0	51.868	51.509	50.818	49.835	48.607	52.176	45.58	48.861	47.033
34.5						0	0	0	48.888	51.382	51.075	50.481	49.622	46.034	49.749	48.296	0	0
33.5					0	0	0	45.637	48.396	48.391	48.124	47.6	51.841	50.867	49.703	0	0	0
32.5		0	0	0	0	0	0	50.175	45.405	45.402	45.162	49.695	49.012	48.129	0	0	0	0
31.5		0	0	0	0	0	0	54.706	47.416	42.411	47.195	41.774	41.153	40.346	39.368	0	0	0
30.5		0	0	0	0	0	51.353	46.733	41.925	41.922	44.225	38.836	38.267	42.524	41.617	0	0	0
29.5		0	0	0	0	0	43.407	41.258	38.934	41.431	46.25	45.891	45.364	39.673	33.831	32.846	36.728	0
28.5			0	0	0	0	37.954	0	38.442	38.44	43.272	37.94	37.449	36.803	41.015	40.086	34.033	32.862
27.5				0	0	0	0	0	0	32.948	35.292	39.981	39.522	38.917	38.172	37.3	36.304	30.192
26.5				0	0	0	0	0	0	0	0	37.019	36.585	36.015	35.313	34.487	33.542	32.484
25.5				0	0	0	0	0	0	0	0	34.055	33.645	33.105	32.441	31.652	30.753	0
24.5		0	0	0	0	0	0	0	0	0	0	0	0	30.184	0	0	0	0
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22.5				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21.5						0	0	0	0	0	0	0	0	0	0	0	0	0
20.5									0	0	0	0	0	0	0	0	0	0
19.5														0	0	0	0	0
18.5															0	0	0	0
17.5																		

WESTERN NORTH ATLANTIC, part 1 LOGISTICS SCENARIO, NEW YORK PERCENT SCORES

latitude/longitude at centers of 1° squares

-64.5	-63.5	-62.5	-61.5	-60.5	-59.5	-58.5	-57.5	-56.5	-55.5	-54.5	-53.5	-52.5	-51.5	-50.5	-49.5	-48.5	-47.5	
																		45.5
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**44.5**
0	0	0	0	0	0	0	24.738	25.067	22.897	20.718	0	0	0	0	0	0		**43.5**
0	0	0	0	0	29.425	27.211	24.995	22.778	20.559	18.34	16.12	0	0	0	0	0		**42.5**
0	0	0	34.036	31.782	29.528	27.273	25.019	25.267	23.016	20.764	18.512	16.266	0	0	0	0		**41.5**
0	35.975	31.193	31.415	31.636	31.857	29.582	27.306	25.032	27.759	25.489	23.218	20.95	0	0	0	0		**40.5**
40.31	38.04	35.764	30.985	28.707	26.425	29.144	26.863	24.582	27.3	25.019	22.738	20.459	0	0	0	0		**39.5**
39.482	37.254	35.014	32.765	28.005	25.74	28.469	31.196	28.92	26.641	24.363	22.082	0	0	0	0	0		**38.5**
38.31	36.153	38.971	36.768	34.546	29.814	27.57	30.319	28.059	25.794	23.523	21.253	0	0	0	0	0		**37.5**
36.844	39.773	37.665	35.524	33.356	31.166	33.961	29.241	27.009	24.768	22.516	20.262	0	0	0	0	0		**36.5**
45.127	38.153	36.129	34.058	31.952	29.819	32.659	25.481	20.783	18.575	16.35	0	0	0	0	0	0		**35.5**
0	0	0	27.4	25.364	23.291	26.185	24.055	21.898	19.725	15.035	0	0	0	0	0	0		**34.5**
0	0	0	0	23.612	26.604	24.557	22.476	20.367	18.237	0	0	0	0	0	0	0		**33.5**
0	0	0	0	31.72	29.776	27.789	20.764	23.704	0	0	0	0	0	0	0	0		**32.5**
0	0	0	0	32.203	35.324	30.899	28.928	0	0	0	0	0	0	0	0	0		**31.5**
0	0	0	36.83	35.078	33.267	31.401	0	0	0	0	0	0	0	0	0	0		**30.5**
0	0	31.161	34.549	32.862	31.112	0	0	0	0	0	0	0	0	0	0	0		**29.5**
31.585	30.205	28.739	32.19	30.567	0	0	0	0	0	0	0	0	0	0	0	0		**28.5**
28.974	27.659	26.253	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**27.5**
26.323	25.065	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**26.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**25.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**24.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**23.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**22.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**21.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**20.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**19.5**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**18.5**
																		17.5

WESTERN NORTH ATLANTIC, part 2 **LOGISTICS SCENARIO, NEW YORK** **PERCENT SCORES**

latitude/longitude at centers of 1° squares

	-98.5	-97.5	-96.5	-95.5	-94.5	-93.5	-92.5	-91.5	-90.5	-89.5	-88.5	-87.5	-86.5	-85.5	-84.5	-83.5	-82.5	-81.5	-80.5	-79.5
31.5																				
30.5										0	0	0	0							
29.5					0	0	0	0	0	0	0	0	0	0	0	0				
28.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
27.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
26.5		0	0	0	0	0	0	0	59.609	62.076	0	0	0	0	0	0	0	0		
25.5		0	0	0	0	58.828	60.175	61.139	61.633	61.606	63.564	57.557	56.177	0	0	0	0	0	0	
24.5		0	0	0	0	56.269	0	0	0	0	0	0	0	57.163	50.459	0	0	0	0	
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0					
21.5		0	0	0	0	0	0	0	0	0	0	0	0							
20.5			0	0	0	0	0	0	0											
19.5			0	0	0	0	0	0												
18.5					0	0														
17.5																				

GULF OF MEXICO

LOGISTICS SCENARIO, NEW ORLEANS

PERCENT SCORES

latitude/longitude at centers of squares

	-150.5	-149.5	-148.5	-147.5	-146.5	-145.5	-144.5	-143.5	-142.5	-141.5	-140.5	-139.5	-138.5	-137.5	-136.5	-135.5	-134.5	-133.5	-132.5	-131.5	-130.5	-129.5	-128.5	-127.5	-126.5	-125.5
60.5																										
59.5		0	0	0	0	0	0	0	0	0	0	0														
58.5		0	0	0	0	0	0	0	0	0	0	0	0	0												
57.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0											
56.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0										
55.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0									
54.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
53.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
52.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
51.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
50.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
49.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38.7
42.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41.19
41.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44.6	43.58
40.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46.32	48.2	45.01	51.73	45.85
39.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37.23	39.41	41.58	43.71	45.81	47.87	49.88	51.82	51.18	50.46
38.5		0	0	0	0	0	0	0	0	0	0	0	0	31.2	36.01	38.31	40.59	42.86	45.11	47.34	49.54	51.71	53.84	55.92	57.93	54.87
37.5		0	0	0	0	0	0	0	0	0	0	0	0	34.19	36.56	38.91	41.26	43.6	45.93	48.24	45.53	47.81	50.05	52.26	59.42	61.52
36.5		0	0	0	0	0	0	0	0	0	0	0	0	34.5	36.91	39.32	41.73	44.12	46.51	48.9	51.27	53.64	50.98	53.3	55.6	57.86
35.5		0	0	0	0	0	0	0	0	0	0	0	0	34.63	37.08	39.53	41.98	44.42	46.87	49.31	51.74	54.17	56.6	59.02	61.42	58.81
34.5		0	0	0	0	0	0	0	0	0	0	0	0	34.58	37.05	39.53	42.01	44.49	46.97	49.45	51.93	54.41	61.88	64.36	66.84	69.31
33.5		0	0	0	0	0	0	0	0	0	0	0	0	34.34	36.84	39.33	41.83	49.33	51.82	54.32	56.82	59.32	61.82	64.32	66.83	69.33
32.5		0	0	0	0	0	0	0	0	0	0	0	0	33.93	41.43	43.93	46.43	48.93	51.43	53.93	56.43	58.92	61.42	63.9	66.38	68.86
31.5		0	0	0	0	0	0	0	0	0	0	0	0	38.34	40.83	43.33	45.83	48.32	50.8	53.29	55.76	58.23	60.68	63.12	68.05	70.44
30.5		0	0	0	0	0	0	0	0	0	0	0	0	37.58	40.06	42.55	45.02	47.49	49.95	52.4	54.84	59.75	62.15	64.52	66.85	69.13
29.5		0	0	0	0	0	0	0	0	0	0	0	0	0	39.13	41.58	44.03	46.47	48.89	51.29	56.17	58.52	60.85	63.12	65.35	67.5
28.5		0	0	0	0	0	0	0	0	0	0	0	0	0	38.03	40.46	42.86	45.26	47.63	52.48	54.79	57.07	59.31	61.48	63.59	65.61
27.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	34.17	41.54	43.88	46.2	48.48	53.23	55.42	57.57	59.64	61.63	63.52
26.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	32.74	35.06	37.35	39.61	46.82	48.99	53.61	55.66	57.63	59.5	61.27
25.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.45	35.68	37.88	40.02	42.11	44.14	48.6	50.47	52.24	53.9
24.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.89	36.02	38.09	40.11	42.06	43.93	40.7	44.87	46.42
23.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29.05	31.06	33	34.87	36.65	38.34	39.92	43.87
22.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.93	35.79	32.58	34.29	35.89	37.39	38.77
21.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.51	35.22	31.85	28.39	29.81	31.1
20.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27.8	29.36	30.82	27.17	28.4
19.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28.21	29.5	25.67
18.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16.5																										

EASTERN NORTH PACIFIC, part 1 LOGISTICS SCENARIO, LOS ANGELES PERCENT SCORES

latitude/longitude at centers of squares

-124.5	-123.5	-122.5	-121.5	-120.5	-119.5	-118.5	-117.5	-116.5	-115.5	-114.5	-113.5	-112.5	-111.5	-110.5	-109.5	-108.5	-107.5	-106.5	-105.5	-104.5	-103.5	-102.5	-101.5	-100.5	
																									60.5
																									59.5
																									58.5
																									57.5
																									56.5
																									55.5
																									54.5
																									53.5
																									52.5
																									51.5
																									50.5
																									49.5
0	0																								48.5
0	0	0																							47.5
0																									46.5
0																									45.5
0																									44.5
0																									43.5
0																									42.5
0																									41.5
0																									40.5
0	0																								39.5
54.2	0	0																							38.5
63.54	60.45	0	0																						37.5
65.06	64.68	66.69	0																						36.5
63.67	68.49	68.25	0	0																					35.5
71.78	69.23	71.68	74.1	0	0																				34.5
71.83	74.33	79.33	81.83	0	0	0	0																		33.5
73.82	76.26	78.66	81	83.21	0	0	0																		32.5
72.79	75.09	77.3	79.36	83.68	90.06	0	0	0		0															31.5
71.34	73.46	75.45	77.23	0	0	0	0	0		0	0														30.5
69.56	71.49	73.26	0	0	0	0	0	0	0		0	0													29.5
67.52	69.28	70.86	72.2	0	0	0	0	0	0		0	0	0												28.5
65.28	66.89	68.3	64.49	0	0	0	0	0	0			0	0	0											27.5
62.9	59.37	60.65	61.72	70.03	0	0	0	0	0	0	0		0	0	0										26.5
55.41	56.76	52.93	53.9	59.62	62.6	62.8	62.73	0	0	0	0	0		0	0	0									25.5
47.83	49.09	50.16	51.04	56.7	59.63	59.81	54.75	54.44	0	0	0	0		0	0	0	0								24.5
45.19	46.36	47.35	48.16	48.76	49.15	51.83	51.77	46.49	45.99	0	0	0	0	0	0	0	0								23.5
42.5	38.59	39.51	40.26	45.82	46.18	46.33	0	0	0	0	0	0	0	0	0	0	0	0							22.5
32.27	35.79	36.65	37.35	42.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						21.5
29.5	30.46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							20.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						19.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				18.5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		17.5
																									16.5

EASTERN NORTH PACIFIC, part 2

LOGISTICS SCENARIO, LOS ANGELES

PERCENT SCORES

APPENDIX B:

GLOSSARY OF GEOLOGICAL AND GEOPHYSICAL TERMS

Definitions of the following terms are, in most cases, modified after definitions found in Holcombe (1977) and Gary et al. (1977).

Abyssal Hill: A generally low-relief, circular of elliptical hill that occurs on the seafloor. Height of the hills are generally in the 50-1000 m range but 100-200 m is average; width is 1-10 km, and slopes are 1-15°.

Abyssal Hill Province: A area of the seafloor that is entirely, or almost entirely, occupied by abyssal hills.

Abyssal Plain: An area of the deep-ocean basin where the seafloor is essentially flat and level: regional gradient is less than 1:1000. These areas occur usually near continental margins and are formed by depositional processes that bury the preexisting topography.

Archipelagic Apron: A generally smooth area surrounding the base of a seamount (or group of islands) that slopes gently away from the seamount. It consists of the erosional debris from the seamount and is built by the same sedimentary process responsible for continental rises and abyssal plains.

Biogenic: Consisting of the remains of living organisms.

Calcium Compensation Depth: The depth below which calcium carbonate dissolves more quickly than it accumulates; about 4500 m, as a general observation.

Carbonate Sediment: A sediment composed predominantly of calcium carbonate (calcite) in the form of organic remains but also as a chemical precipitate (the latter form usually occurs in shallow, warm waters).

Clay: A particle that is smaller than 1/256 mm. Although not technically accurate, the term "clay" is often used when referring to clay minerals.

Clay Minerals: A group of minerals that are formed by the alteration (weathering) of silicate-rich rocks. Individual clay mineral particles are very small in size (less than 1/256 mm)) and, as a result, are easily transported great distances by wind and water currents. In the ocean they settle to the bottom very slowly where they become part of the pelagic sediment that coats the seafloor.

Coastal Plain: The broad, gently sloping lowland areas around the edges of oceans or large bodies of water. In the case of continents, it may be thought of as the exposed areas of the continental shelf.

Continental Crust: Low-density rock material that underlies the continents and, together with oceanic crust, forms the outermost or surface layer of the solid Earth; it is thick (25–70 km) relative to oceanic crust.

Continental Rise: The gently sloping, generally smooth part of the continental margin that lies between the continental slope and deep-ocean floor (usually an abyssal plain).

Continental Shelf: The shallow, but gradually deepening, submerged areas adjacent to continents that extend from the shoreline out to where there is a marked increase of slope to greater depth.

Continental Slope: The descending slope seaward from the edge of the continental shelf.

Contour Currents: Generally deep-flowing currents that follow the contours of the seafloor.

Coccoliths: Tiny (3 microns) button-like plates consisting of calcium carbonate that are the outer skeletal remains of a coccolithophore which is an algae.

Crystalline Basement Rocks: The complex of igneous and metamorphic rocks that compose the upper crust of the Earth and are usually buried beneath sedimentary deposits.

Current Traction: A mode of transportation in which the sediment particles are rolled, slid, bounced, etc., along the seafloor by currents.

Deep-Sea Fan (Submarine Fan): A relatively smooth cone, or fan-shaped feature located on the deep seafloor with its apex at the mouth of a submarine canyon, or lying directly seaward of a large river (e.g., the Mississippi Fan).

Diapir: A structure or body (e.g., dome) that resulted from a material (e.g., salt, mud) being able to flow and thus being forced into and/or through the overlying sedimentary cover. The diapir may cause the overlying sediment layers to bow upward or may actually break through the layers.

Distal: Far from the point of origin.

Folds: A series of ridge-like flexures or undulations produced in rocks by usually compressional forces.

Foraminifera Test: An external shell belonging to, in this case, a foraminifera (protozoan) and consisting of calcium carbonate (calcite).

Fracture Zones: Long (up to 3500 km), narrow (10-100 km) "cuts" in the deep-ocean floor that are oriented at roughly right-angles to, and cut across, mid-ocean ridges. Fracture zones feature an axial trough with steep, irregular sides consisting terraces, seamounts, and ridges.

Graded Bedding: A type of bedding or layering in which each layer displays a gradual change in particle or grain size from large grains at the bottom to small at the top. The basis idea is that in a suspension consisting of various grain sizes, the large grains, usually being heavier, settle out first followed by successively smaller grains.

Hemipelagic: Consisting of appreciable, but not totally, amounts of land-derived (terrigenous) erosional debris.

Levee: An embankment of sediment bordering the sides of a deep-sea fan valley or channel. It is analogous to the levees that border rivers on land.

Marginal Trench: A narrow, elongate depression roughly parallel to and situated at the base of a continental margin or island arc. They contain the deepest places on the seafloor. According to the hypothesis of seafloor spreading, old seafloor is consumed in marginal trenches.

Mid-Ocean Ridge: A continuous, undersea mountain range that extends throughout all the oceans. Generally, it is located in the middle part of the oceans. It features a deep axial valley that is bounded by steep, rugged sides. According to the hypothesis of seafloor spreading, new oceanic crust is generated at mid-ocean ridges: hence, they are seismically active features.

Mud: A general term used to describe a sediment consisting of sand, silt, and clay where no particular component dominates.

Oceanic Crust: High-density rock material that underlies the ocean basins and, together with continental crust, forms the outermost layer of the solid Earth; it is thin (4-9 km) relative to continental crust.

Pelagic Deposition: The slow, even accumulation of fine-grained sediment on the deep-ocean floor.

Pelagic Sediment (deposit): Fine-grained, often wind transported, terrigenous material (typically clay minerals) and biogenic material (e.g., calcite and silica tests of organisms) produced in the surface waters of the ocean that have slowly settled (i.e., pelagic deposition) through several thousand meters of the water before coming to rest on the seafloor.

Red Clay: An extremely fine-grained, pelagic deposit that has accumulated very slowly (a few mm/1000 yrs) in the deeper parts or the ocean. In fact, it is reddish brown to brown in color. The North Pacific is considered to be a red clay province.

Rift: A narrow cleft, fissure, or "crack" that results from the Earth being parted by tensional forces (e.g., the rift valley that runs down the center of a mid-ocean ridge).

Salt Dome (diapirs): A body of salt that, because of its low density, has flowed upward, causing the overlying sedimentary layers to bow upward and rupture. Salt domes along the Gulf Coast of the U.S. are commonly circular in map-view, average 3 km in diameter (but never larger than 30 km), and have migrated upward 10 km in some cases.

Sand: A grain that ranges in size from 1/16 mm to 2 mm.

Silt: A grain that ranges in size from 1/256 mm to 1/16 mm.

Slide: The mass movement of sediment down a slope along a glide plane, i.e., there is no rotation. Generally, slides move greater distances downslope than slumps and there is greater distortion of the sediments.

Slump: The downslope movement of a large block or mass of sediment with minimal translation and internal distortion of the sediment. The movement is rotational in that the rear of the block moves down and the front is forced up.

Stratigraphic Record: The geologic history as preserved in a chronological sequence of sedimentary layers.

Strata: The plural of stratum which means layer.

Submarine Canyon: A long, narrow, deep, steep-sided valley that cuts into a continental slope and shelf. Major canyons usually have tributary canyons and comprise a canyon system.

Terrigenous Sediment: Sediment that is derived from the erosion of land areas.

Textural: Relating to the coarseness or fineness (i.e., size) of the grains or particles making up a sediment.

Turbidite: The layer of sediment deposited by a turbidity current.

Turbidity Current: A bottom-flowing, gravity-driven current laden with suspended sediment that causes it to have a density greater than the surrounding water. It is capable of moving at great speed (90 km/hr) down a slope and is usually contained within a submarine canyon. Upon exiting the canyon, turbidity currents spread out over the ocean-basin floor depositing a blanket-like layer of sediment.

Unleveed: Lacking natural levees.

Upwelling: The rising of deep, usually cold and nutrient-rich, water to the surface of the ocean where it displaces the surface waters.

Volcanogenic Sediment: Sediments that are derived from volcanic sources.